Chapter 7
Subsurface Geophysical Methods

7-1. General In-hole Logging Procedures

a. Introduction. Borehole geophysics, as defined here, is the science of recording and analyzing measurements in boreholes or wells, for determining physical and chemical properties of soils and rocks. The purpose of this section is to provide the basic information necessary to apply the most useful geophysical well logs for the solution of problems in groundwater, the environmental field, and for engineering applications. Some of the objectives of geophysical well logging are:

(1) Identification of lithology and stratigraphic correlation.

(2) Measuring porosity, permeability, bulk density, and elastic properties.

(3) Characterizing fractures and secondary porosity.

(4) Determining water quality.

(5) Identifying contaminant plumes.

(6) Verifying well construction.

Space limitations prevent a comprehensive discussion of the various logging techniques; references are included for those who need further information on specific techniques (Keys 1990). Although the U.S. Government and some private industry have been converting to the metric system for logging equipment and log measuring units, the inch-pound (IP) system is still standard in the United States. In this manual, the IP system is used where IP is the standard for presently used equipment.

b. Benefits of logging. The main objective of borehole geophysics is to obtain more information about the subsurface than can be obtained from drilling, sampling, and testing. Although drilling a test hole or well is an expensive procedure, it provides access to the subsurface where vertical profiles or records of many different kinds of data can be acquired.

(1) Geophysical logs provide continuous analog or digital records of in situ properties of soils and rocks, their contained fluids, and well construction. Logs may be interpreted in terms of: lithology, thickness, and continuity of aquifers and confining beds; permeability, porosity, bulk density, resistivity, moisture content, and specific yield; and the source, movement, chemical and physical characteristics of groundwater and the integrity of well construction. Log data are repeatable over a long period of time, and comparable, even when measured with different equipment. Repeatability and comparability provide the basis for measuring changes in a groundwater system with time. Changes in an aquifer matrix, such as in porosity by plugging, or changes in water quality, such as in salinity or temperature, may be recorded. Thus, logs may be used to establish baseline-aquifer characteristics to determine how substantial future changes may be or what degradation may have already occurred. Logs that are digitized in the field or later in the office may be corrected rapidly, collated, and analyzed with computers.

(2) Some borehole geophysical tools sample or investigate a volume of rock many times larger than core or cuttings that may have been extracted from the borehole. Some probes record data from rock beyond that disturbed by the drilling process. Samples provide point data from laboratory analysis. In contrast, borehole logs usually are continuous data, and can be analyzed in real time at the well site to guide completion or testing procedures. Unlike descriptive logs written by a driller or geologist, which are limited by their authors' experience and purpose and are highly subjective, geophysical logs may provide information on some characteristic not recognized at the time of geophysical logging. Data from geophysical logs are useful in the development of digital models of aquifers and in the design of groundwater supply, recharge, or disposal systems. A log analyst with the proper background data on the area being studied can provide reasonable estimates of hydraulic properties needed for these purposes. Stratigraphic correlation is a common use of geophysical logs; logs also permit the lateral extrapolation of quantitative data from test or core holes. Using logs, a data point in a well can be extended in three dimensions to increase its value greatly. Many techniques used in surface geophysics are related closely to techniques in borehole geophysics, and the two are considered together when setting up comprehensive groundwater, environmental, or engineering investigations. Geophysical logs, such as acoustic-velocity and resistivity, can provide detailed profiles of data that are useful in interpreting surface surveys, such as seismic and resistivity surveys.

c. Limitations of logging.

(1) Geophysical logging cannot replace sampling completely, because some information is needed on each new area to aid log analysis. A log analyst cannot

evaluate a suite of logs properly without information on the local geology. Logs do not have a unique response; for example, high gamma radiation from shale is indistinguishable from that produced by granite. To maximize results from logs, at least one core hole should be drilled in each depositional basin or unique aquifer system. If coring the entire interval of interest is too expensive, then intervals for coring and laboratory analysis can be selected on the basis of geophysical logs of a nearby hole. Laboratory analysis of core is essential either for direct calibration of logs or for checking calibration carried out by other means. Calibration of logs carried out in one rock type may not be valid in other rock types because of the effect of chemical composition of the rock matrix.

(2) In spite of the existence of many equations for log interpretation and charts that provide values like porosity, log analysis still is affected by many variables that are not completely understood. Correct interpretation of logs is based on a thorough understanding of the principles of each technique. For this reason, interpretation of logs in the petroleum industry largely is done by professional log analysts. In contrast, very few log analysts are working in the environmental and engineering fields so interpretation of logs for these applications often is carried out by those conducting the investigation.

(3) A thorough understanding of the theory and principles of operation of logging equipment is essential for both logging operators and log analysts. An equipment operator needs to know enough about how each system works to be able to recognize and correct problems in the field and to select the proper equipment configuration for each new logging environment. A log analyst needs to be able to recognize malfunctions on logs and logs that were not run properly. The maximum benefit is usually derived from a logging operation where operators and analysts work together in the truck to select the most effective adjustments for each log.

d. Cost of logging. Cost of logging can be reduced significantly by running only those logs that offer the best possibility of providing the answers sought. Further reductions in cost can be achieved by logging only those wells that are properly located and constructed to maximize results from logging. In contrast, more money needs to be spent on log analysis. More time may be required to analyze a suite of logs for maximum return than to run the logs; too often this time is not budgeted when the project is planned.

e. Planning a logging program.

(1) A logging program must be properly planned to be of maximum benefit. Borehole geophysics is frequently applied to environmental investigations, such as hydrogeology to aid site selection, monitoring, determining well construction, and planning remediation. In planning a logging program for environmental applications, one of the most difficult questions to answer is what geophysical logs will provide the most information for the funds available. There are several important steps in the decision-making process.

(a) What are the project objectives?

(b) What is the hydrogeology of the site?

(c) How will test holes be drilled and wells constructed?

(d) Who will do the logging and log analysis?

(e) What are the financial limitations and how else might some of this data be obtained?

The log selection process needs to start at the time of the initial work plan.

(2) In addition to selecting the general types of logs to be run, many varieties of some logging tools exist (e.g., resistivity, flowmeter, and caliper). The basic information needed to simplify the selection process among the more commonly used logs is provided in Table 7-1 (Keys, Crowder, and Henrich 1993). Decisions on what logs to be run should not be based on this table alone. Table 7-1 should only be used to select logs that should be investigated further. The logs selected should meet specific project objectives, provide the necessary information in the rock units to be drilled, and consider the planned well construction.

f. Log analysis.

(1) In recent years, computer techniques have dominated log analysis; however, this development has not changed the basic requirements for getting the most information from logs. First, background information on each new hydrogeologic environment is essential where logs are to be used. The amount and kind of background data needed are functions of the objectives of the program.

Table 7-1
Log Selection Chart for Geological Applications Using Common Geophysical Logs (Keys, Crowder, and Henrich 1993)

Required Hole Conditions

- ■ = Cased fluid-filled hole
- ♦ = Clear fluid or dry cased hole
- □ = Screened or open fluid-filled hole
- ◊ = Clear fluid or dry open hole
- † = steel casing only
- Δ = Active nuclear log to be run in stable holes
- ★ = Open or non-conductive cased holes, dry or fluid filled
- ✓ = No restrictions
- ● = Open fluid-filled hole only
- ? = Possible applications

	Measurement →	ACOUSTIC		ELECTRIC & INDUCTION					FLUID LOGS				RADIOACTIVE or NUCLEAR				OTHER METHODS			
	Information Desired	Acoustic Televiewer	Acoustic Velocity Δt, CBL, VDL, FWS	Induced Polarization	Multi-electrode Resistivity Normal, Lateral, Micro Guard Resistivity	Single Point Resistance	Spontaneous Potential	Induction (Conductivity)	Flow Meter	Fluid Resistivity	Fluid Sampler	Temperature, Differential Temp.	Gamma-Gamma Density	Gamma	Neutron	Spectral Gamma	Borehole Video	Caliper	Casing Collar Locator	Deviation
Lithology & Correlation	Bed/Aquifer thickness; correlation, structure	●	●		●	●	●	★					Δ	✓	Δ	✓	◊	✓		
	Lithology - Depositional environment	?	●		●	●	●	★					Δ	✓	Δ	✓	◊	✓		
	Shale or Clay Content			●	●		●	★					Δ	✓	Δ	✓				
	Bulk Density												Δ							
	Formation Resistivity				●			★												
	Injection/Production Profiles				?			?	□	□		□	Δ		Δ					
	Permeability estimates		●						□	□		□		✓						
	Porosity (amount & type)	●	●		●			★					Δ		Δ					
	Mineral Identification			●									Δ			✓				
	Potassium-Uranium-Thorium content (KUT)															✓				
Rock Structure	Strike & Dip of bedding	●															◊			✓
	Fracture detection (no. of fractures), RQD	●	●		●	●											◊	✓		
	Fracture Orientation & character	●															◊			✓
	Thin bed resolution	●			?	●											◊	✓		
Fluid Parameters	Borehole Fluid characteristics								?	□	□	□								
	Fluid Flow						●		□	□		□					◊			
	Formation Water Quality				●		●	★			□									
	Moisture Content - water Sat.				?			?					Δ		Δ					
	Temperature		?									□								
	Water level & water table	●	●		●	●	●	?		□		□	Δ		Δ		◊			
Borehole Parameters	Casing evaluation Integrity, leaks, damage, Screen location	■	■					?	■			■					♦	✓	†	
	Deviation of borehole																			✓
	Diameter of borehole	●																✓		
	Examination behind casing		●					★					Δ		Δ					
	Location of debris in wells	●															♦	✓	✓	
	Well completion evaluation e.g. Cement Bond, Seal location, Grout location	?	■					★					Δ	✓	Δ					

Second, the suite of logs to be run should not only be based on project objectives but also on knowledge of the synergistic nature of logs. Two logs may provide answers that may not be possible with either log separately, and each additional log may add much more to a total understanding of the system. Third, logs need to be selected, run, and analyzed on the basis of a thorough understanding of the principles of each log, even if the final results come out of a computer. The process of log analysis can be simplified into several steps, as follows:

(a) Data processing, which includes depth matching, merging all logs and other data from a single well, and editing and smoothing the data set.

(b) Correction of borehole effects and other errors.

(c) Conversion of log measurements to hydrogeologic and engineering parameters of interest, such as porosity.

(d) Combining logs and other data from all wells on a project so the data can be extrapolated laterally in sections or on maps.

(2) Qualitative analysis. Logs were first used for the identification of rock and fluid types, their lateral correlation, and the selection of likely producing intervals for well completion; these uses are still vital today in many fields. Qualitative log analysis is based mostly on knowledge of the local geology and hydrology, rather than on log-response charts or computer plots. Examination of outcrops, core, and cuttings, coupled with an understanding of log response, will permit the identification and correlation of known aquifers and confining beds.

(a) Lithologic interpretation of logs needs to be checked against data from other sources, because geophysical logs do not have a unique response. This requirement is also true of stratigraphic correlation, where gross errors can be made by just "matching the wiggles." Correlation by matching log character can be done without understanding the response to lithology, but this approach can lead to erroneous results. Even within one depositional basin, the response of one type of log may shift from lateral facies changes. For example, the feldspar content of a sandstone may increase toward a granitic source area, which probably would cause an increase in the radioactivity measured by gamma logs. This measurement might be interpreted mistakenly as an increase in clay content unless other logs or data were available. For this reason, the synergism of composite-log interpretation is stressed in this manual. Logs should be interpreted as an assemblage of data, not singly, to increase the accuracy of analysis.

(b) Accuracy of qualitative interpretation usually improves with an increase in the number of wells that are logged in an area and the amount of available sample data. A gradual change in log response across a depositional basin may indicate a facies change. One anomalous log caused by unusual hole conditions may be identifiable when compared with a number of logs with consistent response; such errors are not likely to repeat. Continuous core or a large number of core samples from one test hole is more useful than a few nonrepresentative samples scattered throughout the section. If continuous coring of one hole cannot be funded, then geophysical logs of a nearby hole can be used to select representative intervals for coring.

(3) Quantitative analysis. Obtaining quantitative data on aquifers or rocks under dam sites is an important objective of many environmental and engineering logging programs; however, the proper steps to ensure reasonable accuracy of the data often are not followed. The scales on logs in physical units, such as percent porosity and bulk density, in grams per cubic centimeter (g/cc), or resistivity, in Ωm, must be determined. Even if the procedures described under log calibration and standardization are followed carefully, corroborating data for the particular rocks and wells logged are needed. Repeatability is ensured by logging selected depth intervals a second time; equipment drift is indicated by changes in response as a function of time or temperature. Because of the effect of rock matrix or specific rock type, calibration in one rock type may not ensure accurate parameter scales in another rock type. For this reason, if the rocks being logged are not the same as those in which the equipment was calibrated, core analyses are needed to check values on the logs. Before any log data are used quantitatively, they must be checked for extraneous effects, such as hole diameter or bed thickness.

(a) Data are of questionable value where hole diameter is significantly greater than bit size, or from intervals where bed thickness is equal to, or less than, the vertical dimension of the volume of investigation for the probe. The volume of investigation is defined for the purposes of this manual as that part of the borehole and surrounding rocks that contributes 90 percent of the signal that is recorded as a log. The radius of investigation is the distance from the sensor out to the 90 percent boundary. These terms do not mean that the volume of investigation is spherical or that the boundary is a sharp cutoff. Instead, a gradual decrease in contribution to the signal occurs with increasing distance from the borehole. The size and shape of the volume of investigation changes in response to varying borehole conditions, the physical properties and geometry of boundaries in the rock matrix and the source to detector spacing. Bed-thickness effects on log response can be best explained using the concept of volume of investigation and its relation to source-to-detector spacing. If a bed is thinner than the vertical dimension of the volume of investigation or thinner than the spacing, the log seldom provides accurate measurement of the thickness or physical properties of that bed because, under these conditions, the volume of investigation includes some of the adjacent beds. From the standpoint of quantitative-log analysis, the best procedure is to eliminate from consideration those depth intervals that demonstrate diameter changes that are significant with respect to the hole diameter response of the logging tool.

(b) Both vertical and horizontal scales on logs need to be selected on the basis of the resolution and accuracy of the data required. Logs obtained by large commercial logging service companies generally have vertical scales of 20 or 50 ft/in., which is not adequate for the detail required in many engineering and environmental studies, where the wells may be only about 100 m deep. Similarly, the horizontal scales on many service-company logs are compressed, to avoid off-scale deflections. Logs digitized in the field will overcome many of these problems and this subject is discussed in detail later. Some logs may be run too fast for the accuracy and thin bed resolution required. When the detector is centered on the contact between two beds of sufficient thickness, half the signal will be derived from one unit, and half from the other; selection of contacts at half amplitude for nuclear logs is based on this fact. If a nuclear or other slow responding log is run too fast, contacts will be hard to pick and will be displaced vertically.

(c) Few logs measure the quantity shown on the horizontal scale directly; for example, the neutron log does not measure porosity; it responds chiefly to hydrogen content. The difference between porosity and hydrogen content can lead to a large porosity error where bound water or hydrocarbons are present. Thus, a knowledge of the principles of log-measuring systems is prerequisite to the accurate quantitative analysis of logs.

(4) Synergistic analysis. Multiple log analysis takes advantage of the synergistic nature of many logs; usually much more can be learned from a suite of logs than from the sum of the logs individually. For example, gypsum cannot be distinguished from anhydrite with either gamma or neutron logs alone, but the two logs together are diagnostic in areas where gypsum and anhydrite are known to exist. They are both very low in radioactive elements, but gypsum has a significant amount of water of crystallization, so it appears as high porosity on the neutron log. In contrast, anhydrite appears as very low porosity on neutron logs. Both minerals will be logged as high resistivity. Computer analysis of logs can be very helpful in identifying such relationships because shading to emphasize differences between logs is easily accomplished.

(a) Examining a suite of logs from a distance is good practice, so that significant trends and shifts in response become more obvious, in contrast to the detail seen up close. Thus replotting logs at different vertical or horizontal scales, using a computer, may bring out features not previously obvious. The suite of logs needs to be examined for similarities and differences, and explanations need to be sought for log response that departs from that anticipated, based on the available background geologic data. When searching for explanations for anomalous log response, first examine the caliper log to determine if an increase in borehole diameter offers a possible reason. Although many logs are titled borehole-compensated or borehole-corrected, almost all logs are affected to some degree by significant changes in borehole diameter. All drill holes, except those drilled in very hard rocks like granite, have thin intervals where hole diameter exceeds bit size sufficiently to cause anomalous log response. Logs usually can be corrected for average borehole diameter, but thin zones of different diameter spanned by the logging tool are difficult to correct. Drilling technique can have a major effect on variations in borehole diameter.

(b) Well construction information also may explain anomalous response, as may information on the mineral or chemical composition of the rock. Casing, cement, and gravel pack have substantial effects on log character. Some logs are designed specifically to provide information on the location and character of casing and cement. These logs are described in the section on well-completion logging.

(5) Computer analysis. Computer analysis of geophysical well logs is now used widely, and if done properly, can contribute significantly to results from log interpretation. The very large amount of data in a suite of well logs cannot easily be collated or condensed in the human mind so that all interrelations can be isolated and used; computer analysis makes this possible. All of the major commercial well-logging service companies offer digitized logs and computer interpretation. Software

packages for log editing and analysis are available that will run on microcomputers with sufficient memory, data storage, and graphics capability. Although the spreadsheet was not designed for log analysis, someone who understands logs can manipulate the data and plot the results (Keys 1986). They do not, however, offer all of the features and flexibility of a program written specifically for log analysis. Programs written for the analysis of oil well logs have many features not needed for environmental and engineering applications and are often more expensive.

(a) Computer analysis of logs offers a number of advantages over other methods used in the past: a large mass of data can be collated and displayed; logs can be corrected and replotted; scales can be changed; smoothing and filtering operations can be carried out; cross-plots can be made between different kinds of logs, and between logs and core data; calibration curves, correlation functions, and ratios can be plotted, as well as cross-section and isopach maps. Finally, these results can be plotted as publication-quality figures at a cost lower than hand plotting. Although all of these manipulations can be carried out by hand, the large quantity of data present in a suite of logs, or in the logs of all wells penetrating an aquifer system, is ideally suited for computer analysis. Figure 7-1 is a computer-generated cross section of three test holes in the Chicago area. The lithology was entered with key terms capitalized so that a column with lithologic symbols could be automatically generated. The correlation lines were sketched using the program and shading between logs can also be added, as in Figure 7-2.

(b) Changing the vertical and horizontal scales of logs independently was almost impossible before computer processing was available; now replotting to produce scales best suited for the intended purpose is a simple matter. Correcting for nonlinear response or changing from a linear to a logarithmic scale are also relatively simple procedures. Most probes output a pulse frequency or a voltage that is related to the desired parameter by an equation which can easily be solved using a computer. Data from probe calibration can be entered in the computer to produce a log in the appropriate environmental units. For example, most neutron logs are recorded in pulses per second, which can be converted to porosity, if proper calibration and standardization data are available. Other logs that might be computed from raw digital data are: differential temperature, acoustic velocity from transit time, and acoustic reflectivity or acoustic caliper.

(c) A computer is suited ideally for correcting logs and plotting them with calibrated scales. Depth correction is required on a large number of logs, and it can be carried out at the same time the computer is being used to make the first plot of digitized data. The most common correction needed is a consistent depth shift for the entire log to make it correlate with other logs of the same well or with core data, but stretching of part of a log can also be carried out.

(d) Another important technique for log analysis is the computer plotting of data obtained from logs against data from other logs, core analyses, or tests. The technique most used is the cross plot, which compares the response of two different logs. A cross plot of transit time from the acoustic-velocity log versus porosity from the neutron log, calibrated for limestone, is given in Figure 7-3. Data were plotted from digitized commercial logs of Madison test well No. 1 drilled by the U.S. Geological Survey in Wyoming. The calibration lines labeled sandstone, limestone, and dolomite were obtained from a plot in a book of log-interpretation charts provided by the company that did the logging. These two logs indicate that two major rock types are in the interval plotted: limestone and dolomite. The group of points to the right of the dolomite line indicates secondary porosity in the dolomite. Another kind of cross-plot that can be made using a computer is illustrated in Figure 7-4. The plot shows a third log variable plotted on the Z axis as a function of the neutron log response. This is the same rock sequence shown in Figures 7-1 and 7-2. When the figure is plotted in color or displayed on a color monitor, the bars in the center track are the same color as the areas on the cross plot representing various lithologic units and the neutron log response is shown by colors. The numerical values in the plot represent the neutron log values.

(6) Digitizing logs. Geophysical logs may be digitized at the well while they are being run or subsequently from the analog record. Onsite digitizing is the most accurate and least expensive; with computers now on some logging trucks, real-time processing of the data may be carried out. Onsite digitizing also provides backup for recovery of data that are lost on the analog recorder because of incorrect selection of scales. Off-scale deflections lost from the analog recorder will be available from the digital record. Some systems permit immediate playback of the digital record to the analog recorder with adjustment of both horizontal and vertical scales. Some probes transmit digital information to the surface and others transmit analog data which are digitized at the surface. There are advantages and disadvantages to both systems but regardless of which is used, logs should be digitized while being run. For most logs it is

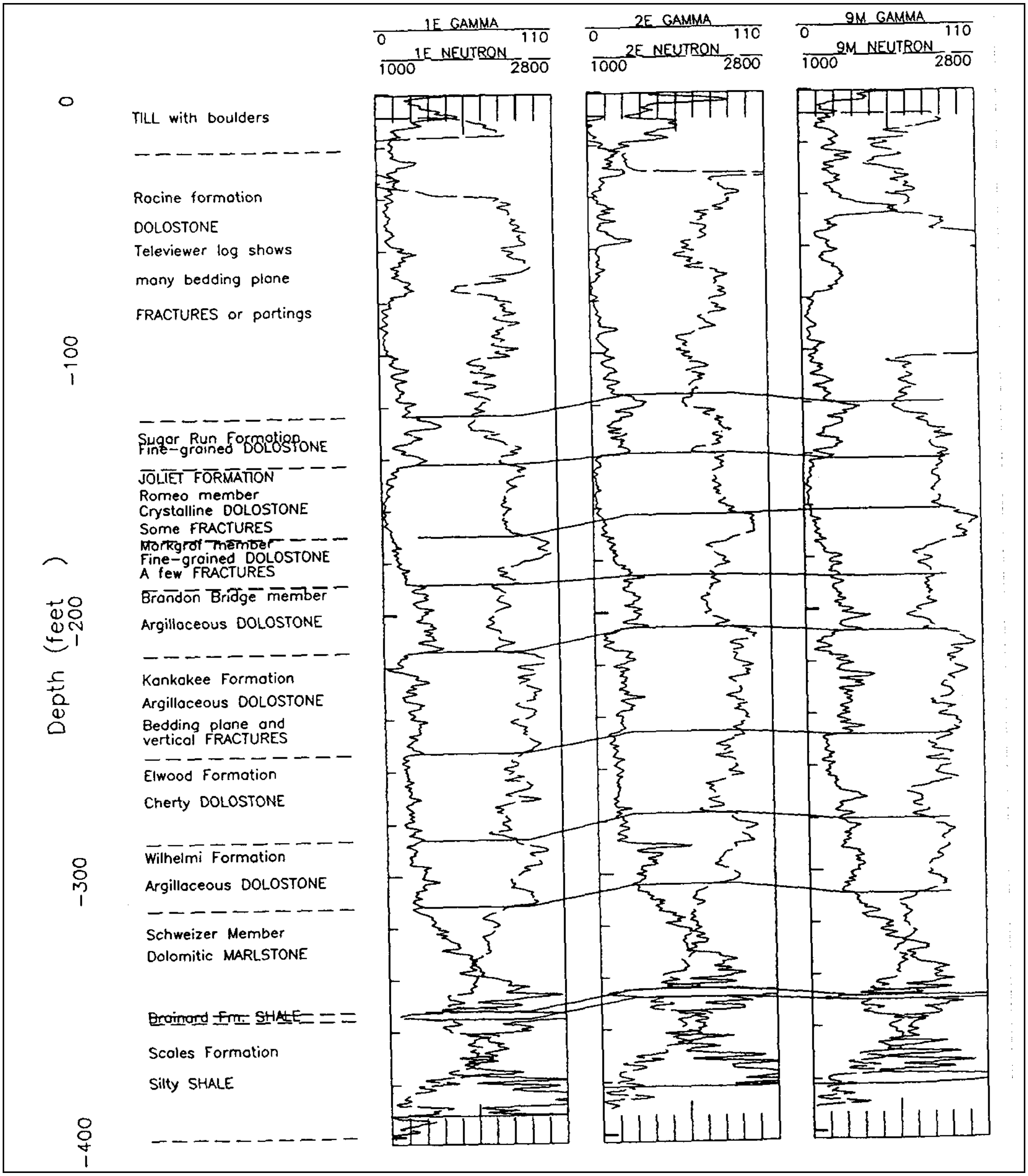


Figure 7-1. Computer plot of gamma and neutron logs of three test holes in the Chicago area, showing stratigraphic correlation based on logs and lithology

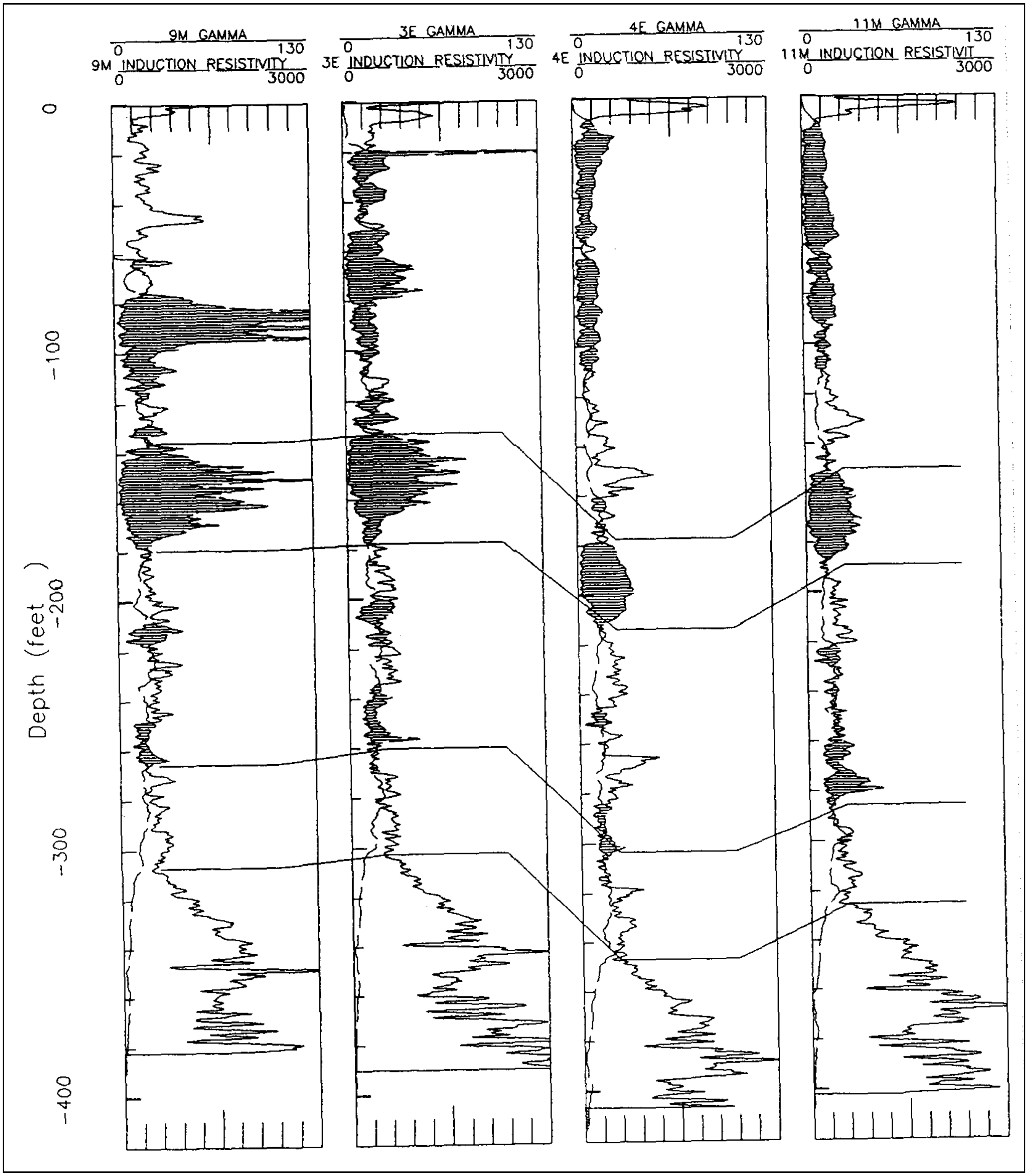


Figure 7-2. Cross section of four test holes in the Chicago area showing correlation enhanced by computer shading between gamma and induction logs

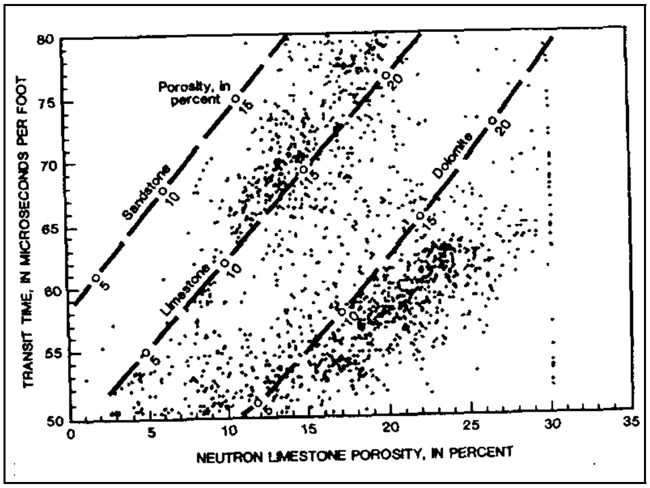


Figure 7-3. Cross plot of acoustic transit times versus neutron porosity, Madison limestone test well No. 1, Wyoming

recommended that the data files be made available immediately to the user in ASCII format because it can be read and reformatted easily by most computers. Some log data, such as acoustic wave forms and televiewer logs, are digitized in other formats.

(a) Sample interval and sample time need to be correctly selected for onsite digitizing of logs. Sample intervals of 0.15 m are used widely in both the petroleum industry and in groundwater hydrology; however, for detailed engineering and environmental investigations, intervals as small as 0.03 m are often used. If too many samples of the data are recorded, some samples can later be erased, and they can be averaged or smoothed; if not enough samples are recorded, needed information may be lost. Sample time is the duration of time over which a single sample is recorded. Sample time may be milliseconds (ms) or less for analog voltages but may be 1 s or longer for pulse signals from a nuclear-logging probe. Digital data may be printed, plotted, or displayed on a computer monitor while the log is being run. An analog display in real time is needed because watching a log develop is one of the best ways to avoid major errors in logging and to optimize probe and data output configuration.

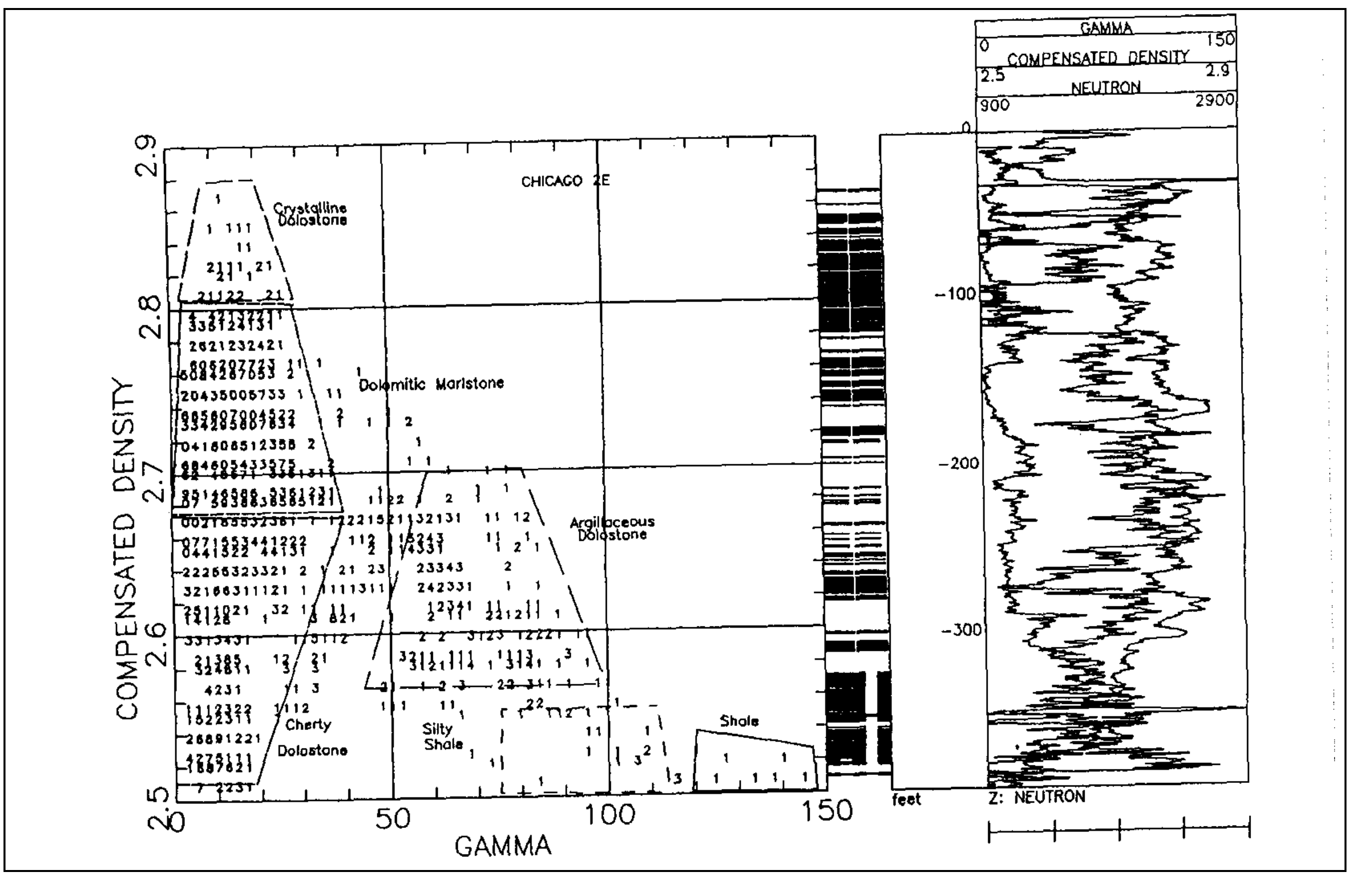


Figure 7-4. Three-dimensional "Z-plot" of gamma, density, and neutron log response of a test hole in the Chicago area

(b) Information on the digital record should be listed on the log heading of the analog plot. This information includes the label on the recording medium, file number, sample interval, time, depth interval recorded, and any calibration information pertinent to the digital record.

(c) Although office digitizing of analog records is expensive and time-consuming, no other choice may exist for old logs. Because of the training needed to digitize logs correctly, particularly multicurve-commercial logs, better and less expensive results usually are obtained from a company specializing in digitizing geophysical logs. To have logs digitized commercially, certain specifications or instructions must be provided to the company with the purchase order. The types of logs to be digitized must be listed, along with the specific curve on each log, the depth interval, the sample interval, and vertical and horizontal scales. If editing of logs is to be done, it must be specified but usually this should be done by the user. In addition to specifying the computer-compatible recording medium, the user can request a printout of all digital data and check plots of the logs. If the check plots are on the same scale as the original, they can be overlaid to verify the accuracy of digitizing.

g. Borehole effects.

(1) The manner in which a test hole or well is drilled, completed, and tested has a significant effect on geophysical logs made in that well (Hodges and Teasdale 1991). One of the objectives of logging is to obtain undisturbed values for such rock properties as porosity, bulk density, acoustic velocity, and resistivity, but the drilling process disturbs the rock near the drill hole to varying degrees. Although a number of different types of logging probes are called borehole compensated or borehole corrected, all probes are affected by the borehole to some degree. Borehole effects on geophysical logs can be divided into those produced by the drilling fluids, mud cake, borehole diameter, and well-construction techniques. All these procedures can be controlled to produce better logs, if that is a high-priority objective. In some situations, it may be cost effective to drill two holes close together -- the first designed to optimize logging and the second cored in the depth intervals suggested by those logs. Even if drilling and completion techniques are beyond control, their effect on log response can be reduced by proper probe selection and an understanding of borehole effects.

(2) All drill holes, except those drilled in very hard rocks like granite, have thin intervals where hole diameter exceeds bit size sufficiently to cause anomalous log response. From the standpoint of quantitative-log analysis, the best procedure is to eliminate from consideration those depth intervals that demonstrate diameter changes that are significant with respect to the hole diameter response of the logging tool.

(3) The difference between a rotary-drilled hole and a nearby core hole in an area where the sedimentary rocks change very little over great distances is shown in Figure 7-5. The core hole was drilled very slowly, with considerable circulation of drilling mud to maximize core recovery. Core recovery was close to 100 percent in these well-cemented mudstones, sandstones, anhydrite, and dolomite. The coring procedure caused significant variations in borehole diameter, partly because of solution

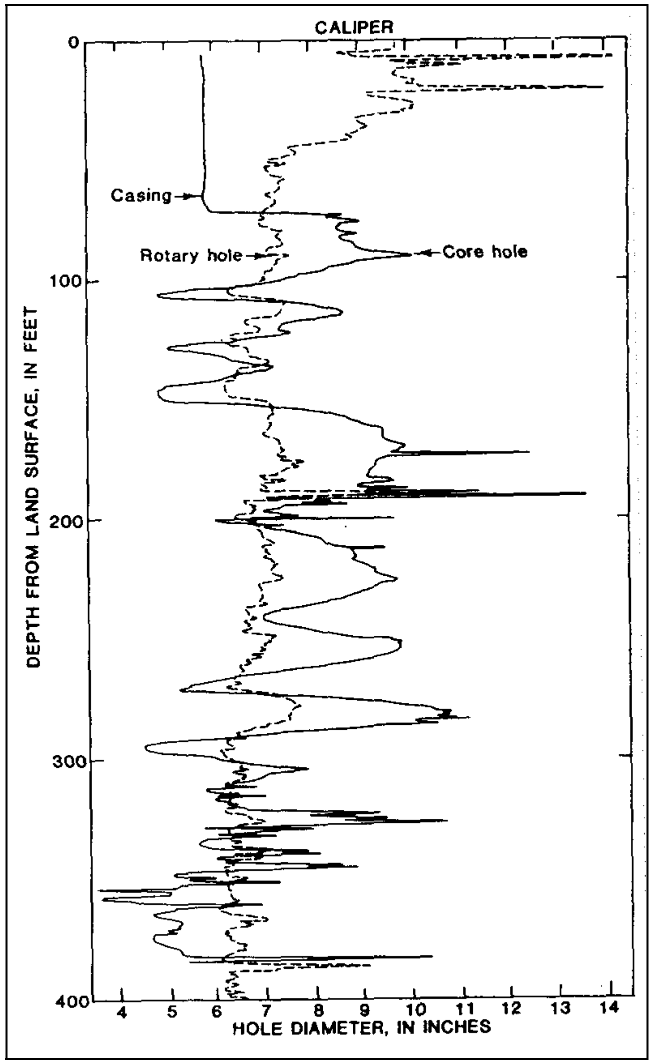


Figure 7-5. Effect of drilling technique on hole diameter. Holes are close together in an area of persistent lithology, Upper Brazos River basin, Texas

of halite cement and veins during the lengthy drilling process, which included numerous trips with the core barrel. The core hole produced some very poor quality logs. The rotary hole was drilled very rapidly to minimize hole-diameter changes. Although increases in hole diameter occurred at the same depths in both holes, the range of diameter was much greater in the core hole. Stratigraphic correlation can be done with caliper logs in this area because hole-diameter changes are closely related to rock type. The very sharp deflections just above 60 m are the result of the solution of halite veins. The very rugose interval below 90 m probably is the result of thin-bedded layers of anhydrite and mudstone.

(4) The hydrostatic pressure of the fluid column is an important factor in preventing caving in poorly consolidated materials. This same pressure can cause invasion of an aquifer by the mud filtrate and the development of a filter cake or mud cake on the wall of the hole. Mud cake may reduce permeability and, thus, change results obtained from various flow-logging devices. The thickness of mud cake often is related to the permeability and porosity of the rocks penetrated. Invasion by drilling fluids may change the conductivity of the pore water and reduce porosity and permeability in the vicinity of the drill hole. Hydraulic fractures can be induced in hard rocks by overpressure during drilling. One technique that is available for determining the extent of alteration of rock and fluid properties adjacent to the borehole is the use of different spacing between source and detector in acoustic or nuclear probes or between electrodes in resistivity probes. Longer spacing usually increases the volume of investigation or increases the percentage of the signal that is derived from material farther from the drill hole. The casing, cement, and gravel pack also have substantial effects on log character. Well completion logs are designed specifically to provide information on the location and character of casing and annular materials.

h. Operation of logging equipment. If maximum benefit is to be obtained from an in-house logger that is purchased or rented on a long-term basis, an operator needs to be trained and assigned sole responsibility for the maintenance and repair of that unit. Logging equipment used by a number of people without adequate training and experience will have higher repair costs and more downtime than equipment assigned to one experienced person.

(1) The larger logging service companies are based almost entirely on oil-well operations; smaller companies rely mostly on environmental, engineering, water-wells or mineral exploration holes. Oil-well logging equipment is larger, and, therefore, more expensive, so that the costs per meter of log are much higher. Oil-well logging probes may be too large for some environmental or engineering test holes, and a large drill rig is needed on the hole to suspend the upper logging sheave. A number of smaller local companies specialize in logging shallower, smaller diameter test holes or wells; some drillers own their own logging equipment. The smaller equipment owned by these companies may not include all the logging techniques available from the commercial service companies. Depth charges, standby time, and mileage costs will be lower for these small companies, but they may not have the calibration facilities common to the larger companies. The low bidder may not provide quality data so proof of ability to perform should be required and a written quality assurance and quality control program should be followed.

(2) The total cost of commercial logging may be difficult for the inexperienced to calculate from price lists, because of the various unit costs involved. Depth and operation charges usually are listed per foot, and a minimum depth is specified. Mileage charges usually prevail over 250 km (150 miles) per round trip. The price of logging on environmental projects may be based on the following:

(a) Daily service charge.

(b) Footage charges.

(c) Mobilization.

(d) Need for special health and safety measures or training.

(e) Equipment decontamination.

(f) Probe and cable loss insurance.

(g) Crew per diem.

(h) Any reports, special processing, or data processing required.

The well needs to be ready for logging when the equipment arrives because standby charges are relatively high. The customer is required to sign an agreement before any logging is done, stating that he assumes full responsibility for the cost of any probes that are lost, the cost of all fishing operations for lost probes, and the cost of any damage to the well. If a radioactive source is lost, fishing is required by law, and the well must be cemented up if the source is not recovered. The use of radioactive sources requires a written agreement which must be addressed in the logging contract.

i. Log-quality control.

(1) Control of the quality of geophysical logs recorded at the well site is the responsibility of all concerned, from the organization providing the logs to the analyst interpreting them; the ultimate responsibility lies with the professional who ordered and accepted the logs. No widely accepted standard or guidelines for log quality control exist at present; however, ASTM is presently working on a set of guidelines. Neither private logging companies nor government logging organizations accept responsibility for the accuracy of the data recorded. Agreements signed prior to logging by commercial companies usually include a disclaimer regarding the accuracy of the log data; therefore, the customer needs to assure that the best practices are followed. To obtain the most useful data, the logging program needs to be discussed early in the planning process with a local representative of the organization that will do the logging.

(2) A geoscientist who understands the project objectives and the local geohydrology needs to be in the logging truck during the entire operation. The observer first will specify the order in which the logs will be run. Usually fluid logs will be run first, if the fluid in the well has had time to reach equilibrium. Nuclear logs always will be run last, or through drill stem if necessary, to reduce the possibility of losing a radioactive source. The observer usually makes preliminary interpretations of the logs as they come off the recorder. Based on immediate analysis, reruns can be requested if problems on the logs can be demonstrated. So many factors must be remembered by the observer to help control the quality of logs that many major oil companies provide a quality-control checklist. Log headings that have blanks for a complete set of well and log data also can serve as partial quality-control checklists. Incomplete log headings may prevent quantitative analysis of logs and make qualitative analysis much more difficult. Copies of digital data and field prints of all logs, including repeat runs, and field calibration or standardization should be left with the project manager before the logging equipment leaves the site. This data should be checked by a qualified person to determine if it is complete and without obvious problems before the logging equipment leaves.

(3) Log headings may be divided into two basic sections: information on the well and data pertaining to the logging equipment and operations. The completed heading needs to be attached to the analog record in the field. A short reference to the log-heading information entered on the digital recording of each log enables the two records to be related. This reference will include the following information, as a minimum: hole number, date, log type, run number. The format of a log heading is not important; the information is essential.

(4) The well-information section of the heading must contain all of the following, if available:

(a) Well name and number.

(b) Location - township, range, section, distance from nearest town, etc.

(c) Owner.

(d) Driller, when drilled, drilling technique, and drilled depth.

(e) Elevation of land surface.

(f) Height of casing above land surface.

(g) Depth reference.

(h) Complete description of all casing, type, size, and depth intervals.

(i) Location of cement, bentonite, perforations, and screens.

(j) Drilled size(s) (or bit size) and depth intervals.

(k) Fluid type, level, resistivity, and temperature.

(5) The log information section of a heading will contain different information for each type of log, although the same heading can be used for similar logs. The following information is needed on the heading for each log:

(a) Type of log, run (___ of ___), date.

(b) Number or description of logging truck.

(c) Logging operator(s), observers.

(d) Probe number and description -- including diameter, type, detector(s), spacing, centralized or decentralized, source type and size, etc.

(e) Logging speed.

(f) Logging scales - vertical (depth) and horizontal, including all changes and depths at which they were made.

(g) Recorder scales - millivolts (span) and positioning.

(h) Module or panel settings - scale, span, position, time constant, discrimination.

(i) Power supply - voltage, current.

(j) Calibration and standardization data - pre- and post-log digital values recorded on heading and analog positions on logs.

(6) List all other logs of the well run on the same date. Also briefly describe all problems or any unusual response during logging; mark at the appropriate depth on the log.

j. Calibration and standardization of logs.

(1) Logs need to be properly calibrated and standardized, if logs are to be used for any type of quantitative analysis or used to measure changes in a groundwater system with time. *Calibration* is considered to be the process of establishing environmental values for log response in a semi-infinite model that closely simulates natural conditions. Environmental units are related to the physical properties of the rock, such as porosity or acoustic velocity. Probe output may be recorded in units, such as pulses per second, that can be converted to environmental units with calibration data. Calibration pits or models are maintained by the larger commercial service companies; these are not readily available for use by other groups. The American Petroleum Institute maintains a limestone-calibration pit for neutron probes and a simulated shale pit for calibrating gamma probes, and a pit for calibrating gamma spectral probes at the University of Houston; these have been accepted internationally as the standards for oil-well logging. Boreholes that have been carefully cored, where the cores have been analyzed quantitatively, also may be used to calibrate logging probes. To reduce depth errors, core recovery in calibration holes needs to approach 100 percent for the intervals cored, and log response can be used to elect samples for laboratory analyses. Because of the possibility of depth errors in both core and logs, and of bed-thickness errors, samples need to be selected in thicker units, where log response does not vary much. It is advisable to have a well for periodic logging to determine if log response is consistent. A core hole is excellent for this purpose.

(2) *Standardization* is the process of checking response of the logging probes in the field, usually before and after logging. Standardization uses some type of a portable field standard that usually is not infinite and may not simulate environmental conditions. Frequent standardization of probes provides the basis for correcting for system drift in output with time and for recognizing other equipment problems. The frequency of log standardization should be related to project objectives - if accurate data are needed, standardization should be more frequent.

k. Logging techniques/tools.

(1) Spontaneous potential logging.

(a) Principles. Spontaneous potential (SP) is one of the oldest logging techniques. It employs very simple equipment to produce a log whose interpretation may be quite complex, particularly in freshwater aquifers. This complexity has led to misuse and misinterpretation of spontaneous potential (SP) logs for groundwater applications. The spontaneous potential log (incorrectly called self potential) is a record of potentials or voltages that develop at the contacts between shale or clay beds and a sand aquifer, where they are penetrated by a drill hole. The natural flow of current and the SP curve or log that would be produced under the salinity conditions given are shown in Figure 7-6. The SP measuring equipment consists of a lead or stainless steel electrode in the well connected through a millivolt meter or comparably sensitive recorder channel to a second electrode that is grounded at the surface (Figure 7-7). The SP electrode usually is incorporated in a probe that makes other types of electric logs simultaneously so it is usually recorded at no

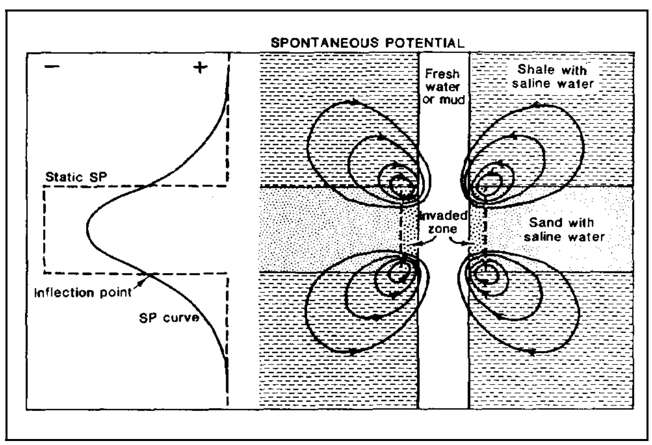


Figure 7-6. Flow of current at typical bed contacts and the resulting spontaneous-potential curve and static values

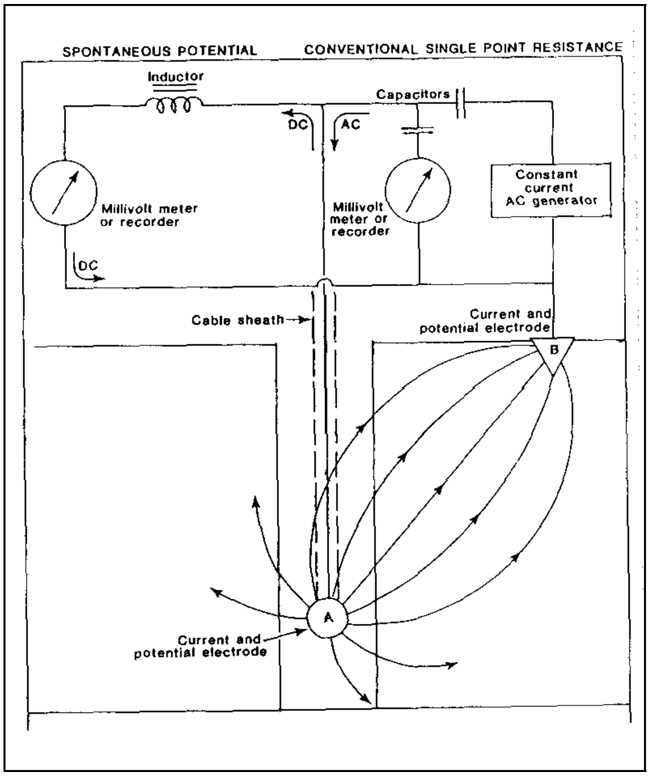


Figure 7-7. System used to make conventional single-point resistance and spontaneous-potential logs

additional cost. Spontaneous potential is a function of the chemical activities of fluids in the borehole and adjacent rocks, the temperature, and the type and amount of clay present; it is not directly related to porosity and permeability. The chief sources of spontaneous potential in a drill hole are electrochemical, electrokinetic, or streaming potentials and redox effects. When the fluid column is fresher than the formation water, current flow and the SP log are as illustrated in Figure 7-6; if the fluid column is more saline than water in the aquifer, current flow and the log will be reversed. Streaming potentials are caused by the movement of an electrolyte through permeable media. In water wells, streaming potential may be significant at depth intervals where water is moving in or out of the hole. These permeable intervals frequently are indicated by rapid oscillations on an otherwise smooth curve. Spontaneous potential logs are recorded in millivolts per unit of chart paper or full scale on the recorder. Any type of accurate millivolt source may be connected across the SP electrodes to provide calibration or standardization at the well. The volume of investigation of an SP sonde is highly variable, because it depends on the resistivity and cross-sectional area of beds intersected by the borehole. Spontaneous potential logs are more affected by stray electrical currents and equipment problems than most other logs. These extraneous effects produce both noise and anomalous deflections on the logs. An increase in borehole diameter or depth of invasion decreases the magnitude of the SP recorded. Obviously, changes in depth of invasion with time will cause changes in periodic SP logs. Because the SP is largely a function of the relation between the salinity of the borehole fluid and the formation water, any changes in either will cause the log to change.

(b) Interpretation and applications. Spontaneous potential logs have been used widely in the petroleum industry for determining lithology, bed thickness, and the salinity of formation water. SP is one of the oldest types of logs, and is still a standard curve included in the left track of most electric logs. The chief limitation that has reduced the application of SP logs to groundwater studies has been the wide range of response characteristics in freshwater environments. As shown in Figure 7-6, if the borehole fluid is fresher than the native interstitial water, a negative SP occurs opposite sand beds; this is the so-called standard response typically found in oil wells. If the salinities are reversed, then the SP response also will be reversed, which will produce a positive SP opposite sand beds. Thus, the range of response possibilities is very large and includes zero SP (straight line), when the salinity of the borehole and interstitial fluids are the same. Lithologic contacts are located on SP logs at the point of curve inflection, where current density is maximum. When the response is typical, a line can be drawn through the positive SP-curve values recorded in shale beds, and a parallel line may be drawn through negative values that represent intervals of clean sand. A typical response of an SP log in a shallow-water well, where the drilling mud was fresher than the water in the aquifers, is shown in Figure 7-8. The maximum positive SP deflections represent intervals of fine-grained material, mostly clay and silt; the maximum negative SP deflections represent coarser sediments. The gradational change from silty clay to fine sand near the bottom of the well is shown by a gradual change on the SP log. The similarity in the character of an SP log and a gamma log under the right salinity conditions also is shown in this figure. Under these conditions, the two types of logs can be used interchangeably for stratigraphic correlation between wells where either the gamma or the SP might not be available in some wells. The similarity between SP and gamma logs also can be used to identify wells where salinity relationships are different from those shown in Figure 7-8. Spontaneous-potential logs have been used widely for determining formation-water resistivity (R_w) in oil wells, but this application is limited in fresh groundwater

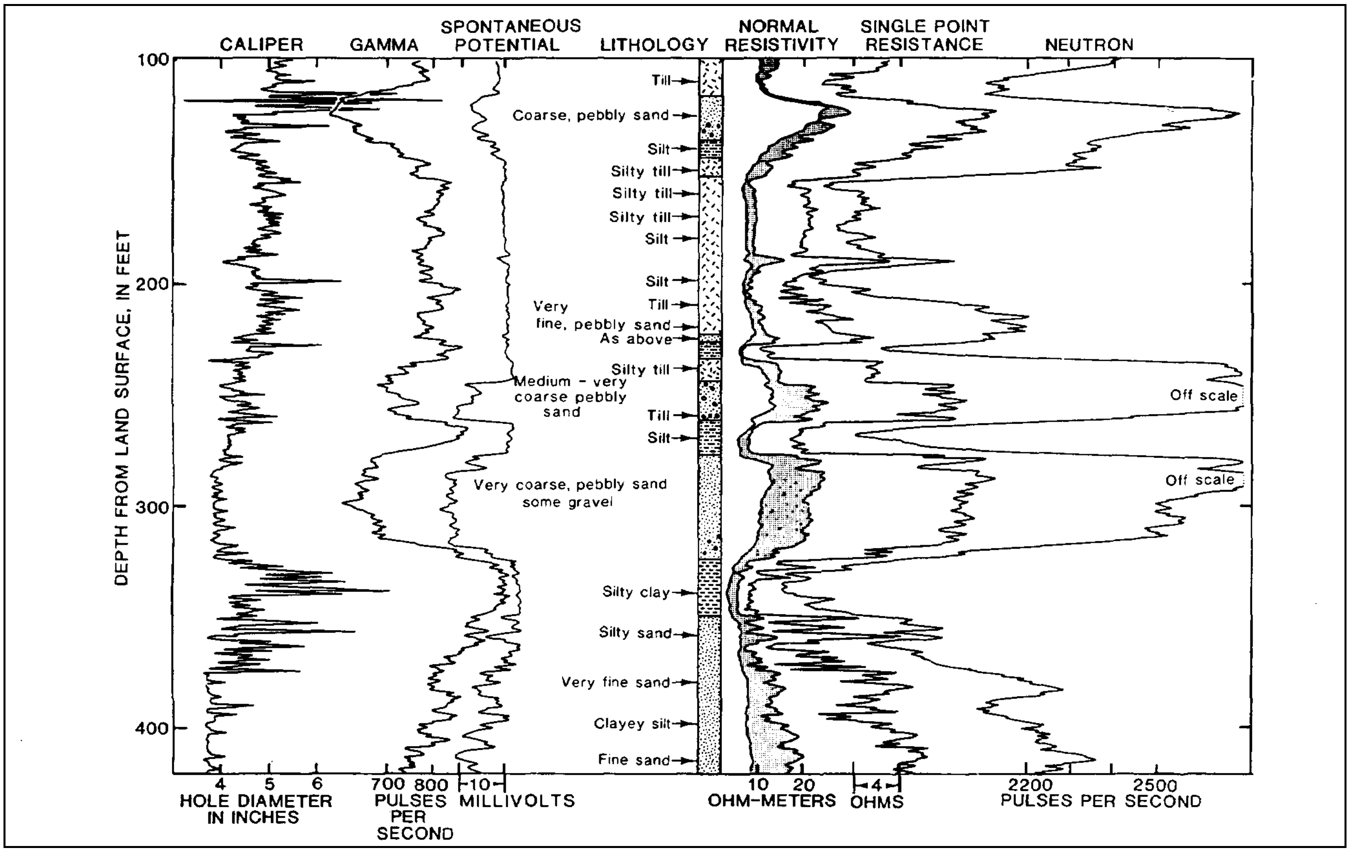


Figure 7-8. Caliper, gamma, spontaneous-potential, normal-resistivity, single-point resistance, and neutron logs compared to lithology; Kipling, Saskatchewan, Canada

systems. In sodium chloride type saline water, the following relation is used to calculate R_w:

$$SP = -K \log (R_m/R_w) \qquad (7\text{-}1)$$

where

SP = log deflection, in mV

$K = 60 + 0.133T$

T = borehole temperature, in degrees Fahrenheit (metric and IP units are mixed for equation validity)

R_m = resistivity of borehole fluid, in Ωm

R_w = resistivity of formation water, in Ωm

The SP deflection is read from a log at a thick sand bed; R_m is measured with a mud-cell or fluid-conductivity log. Temperature may be obtained from a log, but it also can be estimated, particularly if bottom-hole temperature is available. The unreliability of determining R_w of fresh water using the SP equation has been discussed by Patten and Bennett (1963) and Guyod (1966). Several conditions must be met if the equation is to be used for groundwater investigations. These conditions are not satisfied in most freshwater wells. The conditions are as follows: Both borehole fluids and formation water need to be sodium chloride solutions. The borehole fluid needs to be quite fresh, with a much higher resistivity than the combined resistivity of the sand and shale; this requirement usually means that the formation or interstitial water must be quite saline. The shales need to be ideal ion-selective membranes, and the sands need to be relatively free of clay. No contribution can be made to the SP from such sources as streaming potential.

(2) Single-point resistance logging.

(a) Principles. The single-point resistance log has been one of the most widely used in non-petroleum logging in the past; it is still useful, in spite of the increased application of more sophisticated techniques. Single-point logs cannot be used for quantitative interpretation, but they are excellent for lithologic information. The equipment to make single-point logs usually is available on most small water-well loggers, but it is almost never available on the larger units used for oil-well logging. The resistance of any medium depends not only on its composition, but also on the cross-sectional area and length of the path through that medium. Single-point resistance systems measure the resistance, in Ω, between an electrode in the well and an electrode at the surface or between two electrodes in the well. Because no provision exists for determining the length or cross-sectional area of the travel path of the current, the measurement is not an intrinsic characteristic of the material between the electrodes. Therefore, single-point resistance logs cannot be related quantitatively to porosity, or to the salinity of water in those pore spaces, even though these two parameters do control the flow of electric current. A schematic diagram of the equipment used to make conventional single-point resistance and spontaneous potential logs is shown in Figure 7-7. The two curves can be recorded simultaneously if a two-channel recorder is available. The same ground and down-hole electrodes (A and B) are used for both logs. Each electrode serves as a current and as a potential sensing electrode for single-point logs. The single-point equipment on the right side of the figure actually measures a potential in volts (*V*) or *mV* which can be converted to resistance by use of Ohm's law, because a constant current is maintained in the system. For the best single-point logs, the electrode in the well needs to have a relatively large diameter, with respect to the hole diameter, because the radius of investigation is a function of electrode diameter. The differential system, with both current and potential electrodes in the probe, which are separated by a thin insulating section, provides much higher resolution logs than the conventional system but is not available on many loggers. Scales on single-point resistance logs are calibrated in Ω per inch of span on the recorder. The volume of investigation of single-point resistance sonde is small, approximately 5 to 10 times the electrode diameter. Single-point logs are greatly affected by changes in well diameter, partly because of the relatively small volume of investigation.

(b) Interpretation and applications. Single-point resistance logs are useful for obtaining information on lithology; the interpretation is straightforward, with the exception of the extraneous effects described previously. Single-point logs have a significant advantage over multi-electrode logs; they do not exhibit reversals as a result of bed-thickness effects. Single-point logs deflect in the proper direction in response to the resistivity of materials adjacent to the electrode, regardless of bed thickness; thus, they have a very high vertical resolution. The response of both differential and conventional single-point logs to fractures is illustrated in Figure 7-9. In this figure, at least one of the logging systems was not properly calibrated, because the scales differ by an order of magnitude. Hole enlargements shown on the caliper log are almost entirely caused by fractures in the crystalline rocks penetrated by this hole. The differential single-point log defines the fractures with much greater resolution than the log made with the conventional system.

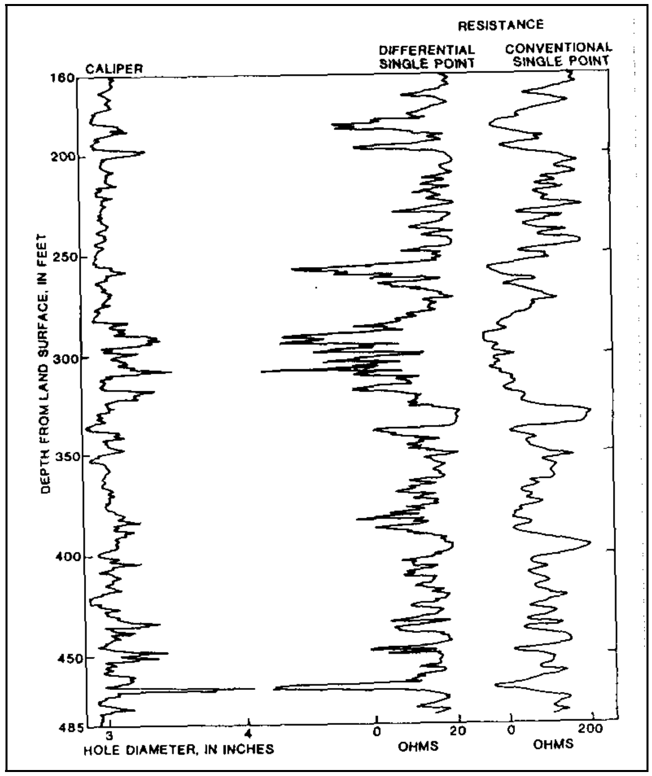


Figure 7-9. Caliper, differential, and conventional single-point resistance logs in a well in fractured crystalline rocks

(3) Normal-resistivity logging.

(a) Principles. Among the various multi-electrode resistivity-logging techniques, normal resistivity is probably the most widely used in groundwater hydrology, even though the long normal log has become rather obsolete in the oil industry. Normal-resistivity logs can be interpreted quantitatively when they are properly calibrated in terms of Ω*m*. Log measurements are converted to apparent resistivity, which may need to be corrected for mud resistivity, bed thickness, borehole diameter, mudcake, and invasion, to arrive at true resistivity. Charts for making these corrections are available in old logging manuals. Figure 7-10 is an example of one of these charts that is used to correct 16-in. normal curves for borehole diameter and mud resistivity. The arrows on this chart show examples of corrections for borehole size and mud resistivity (R_m). If the resistivity from a 16-in. normal curve divided by the mud resistivity is 50 in a 10-in. borehole, the ratio will be 60 in an 8-in. borehole. If the apparent resistivity on a 16-in. normal log is 60 Ω*m* and the R_m is 0.5 Ω*m* in a 9-in. well, the ratio on the X-axis is 195. The corrected log value is 97.5 Ω*m* at formation temperature. Temperature corrections and conversion to conductivity and to equivalent sodium chloride concentrations can be made using Figure 7-11. To make corrections, the user should follow along isosalinity lines because only resistivity, or its inverse, conductivity, changes as a function of temperature, not ionic concentrations.

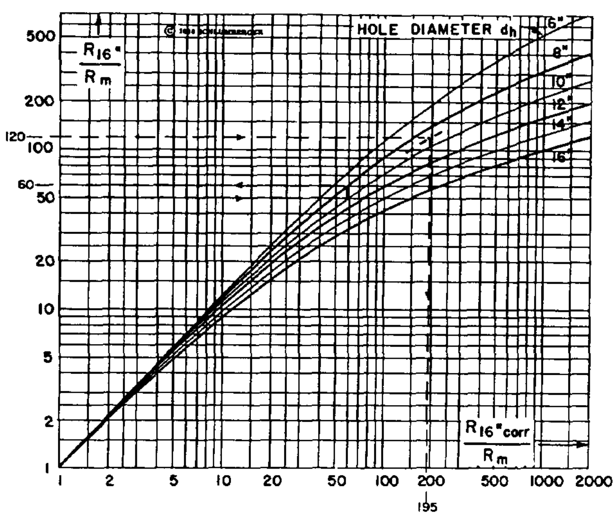


Figure 7-10. Borehole correction chart for 16-in. normal resistivity log (copyright permission granted by Schlumberger)

(b) Definition. By definition, resistivity is a function of the dimensions of the material being measured; therefore, it is an intrinsic property of that material. Resistivity is defined by the formula:

$$R = rS/L = (\Omega \times m \times m/m) = (\Omega \times m) = (\Omega m) \tag{7-2}$$

where

R = resistivity, in Ω*m*

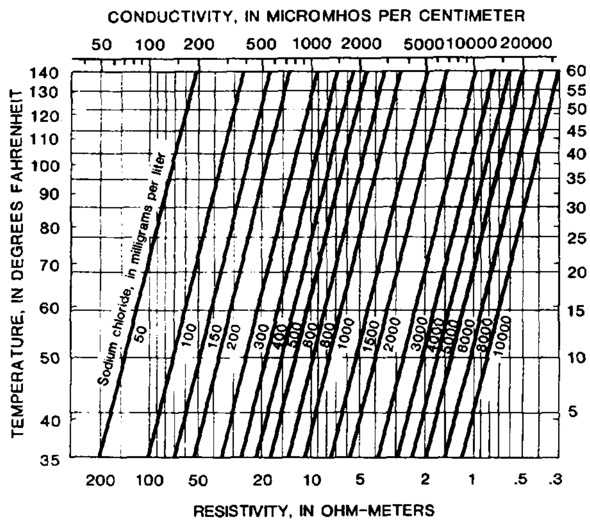


Figure 7-11. Electrically equivalent sodium chloride solution plotted as a function of conductivity or resistivity and temperature

r = resistance, in Ω

S = cross section, in square meters

L = length, in m

The principles of measuring resistivity are illustrated in Figure 7-12. If 1 amp of current from a 10-*V* battery is passed through a 1-m^3 block of material, and the drop in potential is 10 *V*, the resistivity of that material is 10 Ω*m*. The current is passed between electrodes A and B, and the voltage drop is measured between potential electrodes M and N, which, in the example, are located 0.1 m apart so that 1 *V* is measured rather than 10 *V*. The current is maintained constant, so that the higher the resistivity between M and N, the greater the voltage drop will be. A commutated DC current is used to avoid polarization of the electrodes that would be caused by the use of direct current.

(c) AM spacing. For normal-resistivity logging, electrodes A and M are located in the well relatively close together, and electrodes B and N are distant from AM and from each other, as shown in Figure 7-13. Electrode configuration may vary in equipment produced by different manufacturers. The electrode spacing, from which the normal curves derive their name, is the distance between A and M, and the depth reference is at the midpoint of this distance. The most common AM spacings are 16 and

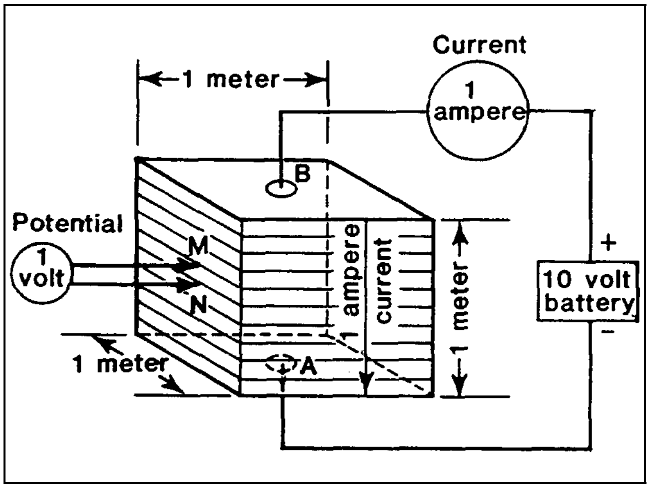


Figure 7-12. Principles of measuring resistivity in Ωm. Example is 10 Ωm

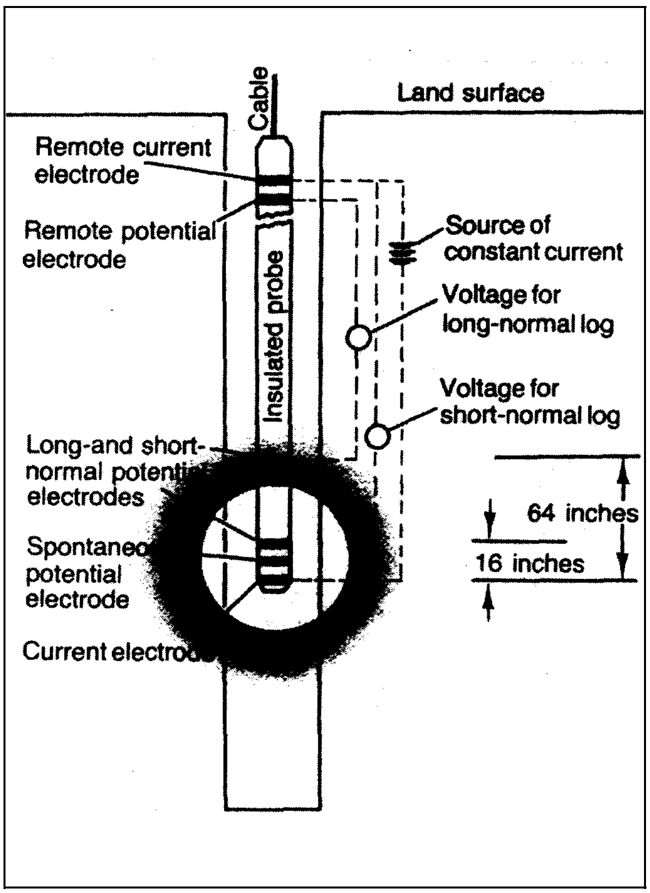


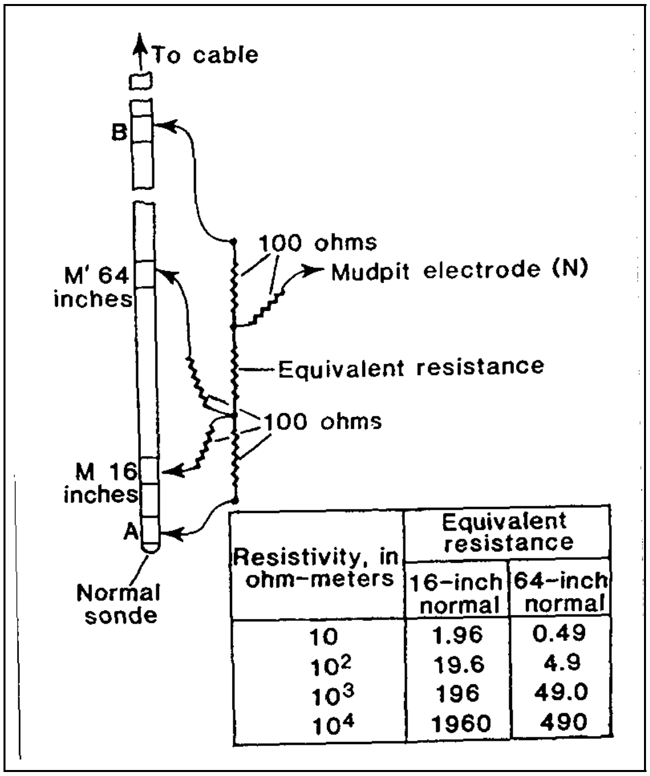
Figure 7-13. System used to make 16- and 64-in. normal-resistivity logs. Shaded areas indicate relative size of volumes of investigation

64 in.; however, some loggers have other spacings available, such as 4, 8, 16, and 32 in. The distance to the B electrode, which is usually on the cable, is approximately 15 m ; it is separated from the AM pair by an insulated section of cable. The N electrode usually is located at the surface, but in some equipment, the locations of the B and N electrodes may be reversed. Constant current is maintained between an electrode at the bottom of the sonde and a remote-current electrode. The voltage for the long normal (64-in.) and the short normal (16-in.) is measured between a potential electrode for each, located on the sonde, and a remote potential electrode. The SP electrode is located between the short normal electrodes. The relative difference between the volumes of material investigated by the two normal systems also is illustrated in Figure 7-13. The volume of investigation of the normal resistivity devices is considered to be a sphere, with a radius approximately twice the AM spacing. This volume changes as a function of the resistivity, so that its size and shape are changing as the well is being logged.

(d) Depth of invasion. Although the depth of invasion is a factor, short normal (16 in. or less) devices are considered to investigate only the invaded zone, and long normal (64-in.) devices are considered to investigate both the invaded zone and the zone where native formation water is found. These phenomena are illustrated in Figure 7-8. In this figure, the area between a 32-in. curve on the left and a 4-in. curve on the right is shaded. The longer spaced curve indicates a lower resistivity farther back in the aquifers than in the invaded zone near the borehole wall, which suggests that the formation water is relatively saline with respect to the borehole fluid.

(e) Calibration. Normal-resistivity logging systems may be calibrated at the surface by placing fixed resistors between the electrodes. The formula used to calculate the resistor values to be substituted in the calibration network shown in Figure 7-14 is given in Keys (1990).

(f) Interpretation. Long normal response is affected significantly by bed thickness; this problem can make the logs quite difficult to interpret. The bed-thickness effect is a function of electrode spacing, as illustrated in Figure 7-15. The theoretical resistivity curve (solid line) and the actual log (dashed line) for a resistive bed, with a thickness six times the AM spacing, is shown in the top part of the figure. Resistivity of the limestone is assumed to be six times that of the shale, which is of infinite



Resistivity, in ohm-meters	Equivalent resistance	
	16-inch normal	64-inch normal
10	1.96	0.49
10^2	19.6	4.9
10^3	196	49.0
10^4	1960	490

Figure 7-14. System for calibrating normal-resistivity equipment

thickness. With a bed thickness six times AM, the recorded resistivity approaches, but does not reach, the true resistivity (R_t); the bed is logged as being one AM spacing thinner than it actually is. The actual logged curve is a rounded version of the theoretical curve, in part because of the effects of the borehole. The log response when the bed thickness is equal to or less than the AM spacing is illustrated in the lower half of Figure 7-15. The curve reverses, and the high-resistivity bed actually appears to have a lower value than the surrounding material. The log does not indicate the correct bed thickness, and high-resistivity anomalies occur both above and below the limestone. Although increasing the spacing to achieve a greater volume of investigation would be desirable, bed-thickness effects would reduce the usefulness of the logs except in very thick lithologic units.

(g) Applications. An important application of normal resistivity logs and other multi-electrode logs is for determining water quality. Normal logs measure apparent resistivity; if true resistivity is to be obtained from these logs they must be corrected with the appropriate charts or departure curves. A summary of these techniques is found in "The Art of Ancient Log Analysis," compiled

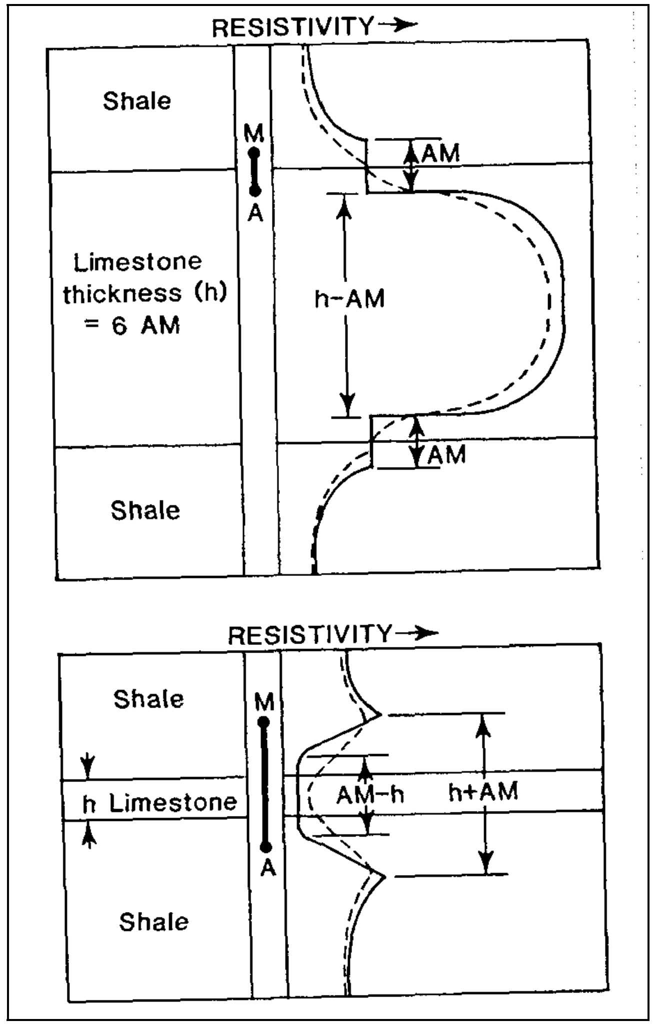


Figure 7-15. Relation of bed thickness to electrode spacing for normal devices at two thicknesses

by the Society of Professional Well Log Analysts (1979). A practical method is based on establishing field-formation resistivity factors (*F*) for aquifers within a limited area, using electric logs and water analyses. After a consistent formation factor is established, the long normal curve, or any other resistivity log that provides a reasonably correct R_t can be used to calculate R_w from the relationship: $F = R_o/R_w$. Under these conditions R_o the resistivity of a rock 100 percent saturated with water, is assumed to approximate R_t, after the appropriate corrections have been made. Resistivities from logs can be converted to standard temperature using Figure 7-11, and the factors listed in Keys (1990) can be used to convert water containing other ions to the electrically equivalent sodium chloride solution. The formation resistivity factor (*F*) also defines the relation between porosity (*Ø*) and resistivity as follows: $F = a/Ø^m = R_o/R_w$, where m is the cementation exponent (Archie's formula). See Jorgensen (1989) for a more complete description of these relations. Using porosity derived from a neutron, gamma-gamma, or acoustic velocity log and R_o from a deep investigating resistivity log, one can determine the resistivity of the formation water in granular sediments. The relation between resistivity from normal logs and the concentration of dissolved solids in groundwater is only valid if the porosity and clay content are relatively uniform. The method does not apply to rocks with a high clay content or with randomly distributed solution openings or fractures. Surface conduction in clay also tends to reduce the resistivity measured. The resistivity logs in Figure 7-8 were used to calculate the quality of the water in aquifers at the Kipling well site in Saskatchewan, Canada. The left trace of the two normal resistivity logs shown is the 32-in. normal, which was used to calculate R_w for three of the shallower aquifers intersected. These aquifers are described as coarse pebbly sand based on side-wall core samples. The 32-in. normal was selected because many of the beds in this area are too thin for longer spacing. Wyllie (1963) describes a method for estimating F from the ratio R_i/R_m; where R_i is the resistivity of the invaded zone from a short normal log like the 4-in.; and R_m is the measured resistivity of the drilling mud. On the basis of the 4-in. curve, F was estimated to be 2.5 for the upper aquifer and 1.8 for the lower two. The true resistivities for the three aquifers obtained from departure curves are 30, 20, and 17 Ωm at depths of 130, 250, and 295 ft, respectively. A formation factor of 3.2 provided good agreement with water quality calculated from SP logs and from laboratory analyses. Using an F of 3.2, R_w was calculated to be 9.4, 6.2, and 5.3 Ωm at 4˚C for the three aquifers. The drilling mud measured 13 Ωm at borehole temperature. The separation of the two normal curves and the SP log response substantiated the fact that the water in the aquifers was more saline than the drilling mud.

(4) Lateral resistivity logging. Lateral logs are made with four electrodes like the normal logs but with a different configuration of the electrodes. The potential electrodes M and N are located 0.8 m apart; the current electrode A is located 5.7 m above the center (O) of the MN spacing in the most common petroleum tool, and 1.8 m in tools used in groundwater. Lateral logs are designed to measure resistivity beyond the invaded zone, which is achieved by using a long electrode spacing. They have several limitations that have restricted their use in environmental and engineering applications. Best results are obtained when bed thickness is greater than twice AO, or more than 12 m for the standard spacing. Although correction charts are available, the logs are difficult to interpret. Anomalies are asymmetrical about a bed, and the amount of distortion is related to bed thickness and the effect of adjacent beds. For these reasons the lateral log is not recommended for most engineering and environmental applications.

(5) Focused-resistivity logging.

(a) Focused-resistivity systems were designed to measure the resistivity of thin beds or high-resistivity rocks in wells containing highly conductive fluids. A number of different types of focused-resistivity systems are used commercially; the names "guard" or "laterolog" are applied to two of these. Focused or guard logs can provide high resolution and great penetration under conditions where other resistivity systems may fail. Focused-resistivity devices use guard electrodes above and below the current electrode to force the current to flow out into the rocks surrounding the well. The depth of investigation is considered to be about three times the length of one guard, so a 6-ft guard should investigate material as far as 5.5 m from the borehole. The sheetlike current pattern of the focused devices increases the resolution and decreases the effect of adjacent beds in comparison with the normal devices.

(b) Microfocused devices include all the focusing and measuring electrodes on a small pad; they have a depth of investigation of only several centimeters. Because the geometric factor, which is related to the electrode spacing, is difficult to calculate for focused devices, calibration usually is carried out in a test well or pit where resistivities are known. When this is done, the voltage recorded can be calibrated directly in terms of resistivity. Zero resistivity can be checked when the entire electrode assembly is within a steel-cased interval of a well that is filled with water.

(c) Correction for bed thickness (h) is only required if h is less than the length of M, which is 6 in. on some common tools. Resistivities on guard logs will approach R_t, and corrections usually will not be required if the following conditions are met: $R_m / R_w < 5$, $R_t / R_m > 50$, and invasion is shallow. If these conditions are not met, correction charts and empirical equations are available for obtaining R_t (Pirson 1963).

(6) Microresistivity logging. A large number of microresistivity devices exist, but all employ short electrode spacing so that they have a shallow depth of investigation. They can be divided into two general groups: focused and non-focused. Both groups employ pads or

some kind of contact electrodes to reduce the effect of the borehole fluid. Non-focused sondes are designed mainly to determine the presence or absence of mud cake, but they also can provide very high-resolution lithologic detail. Names used for these logs include microlog, minilog, contact log, and micro-survey log. Focused microresistivity devices also use small electrodes mounted on a rubber-covered pad forced to contact the wall of the hole hydraulically or with heavy spring pressure. The electrodes are a series of concentric rings less than 1 in. apart that function in a manner analogous to a laterolog system. The radius of investigation is from 76 to 127 mm (3 to 5 in.), which provides excellent lithologic detail beyond the mudcake, but probably is still within the invaded zone.

(7) Dipmeter logging.

(a) The dipmeter includes a variety of wall-contact microresistivity devices that are widely used in oil exploration to provide data on the strike and dip of bedding planes. The most advanced dipmeters employ four pads located 90 deg apart, oriented with respect to magnetic north by a magnetometer in the sonde. Older dipmeters used three pads, 120 deg apart. The modern dipmeter provides a large amount of information from a complex tool, so it is an expensive log to run. Furthermore, because of the amount and complexity of the data, the maximum benefit is derived from computer analysis and plotting of the results. Interpretation is based on the correlation of resistivity anomalies detected by the individual arms, and the calculation of the true depth at which those anomalies occur. The log from a four-arm tool has four resistivity curves and two caliper traces, which are recorded between opposite arms, so that the ellipticity of the hole can be determined. The Formation Microscanner is related to the dipmeter. It uses arrays of small electrodes to provide oriented conductance images of segments of the borehole wall scanned by the pads. These images are similar to an acoustic televiewer log but they do not include the entire borehole wall. The microscanner may be preferable in heavy muds or deviated holes.

(b) Although strike and dip can be determined from the analog record at the well using a stereo net, complete analysis is only possible with a computer. A computer program can make all necessary orientation and depth corrections and search for correlation between curves with a selected search interval. Computer output usually consists of a graphic plot and a listing of results. The graphic plot displays the depth, true-dip angle, and direction of dip by means of a symbol called a “tadpole” or an arrow. The angle and direction of the tool also is displayed. Linear polar plots and cylindrical plots of the data also are available. A printout that lists all the interpreted data points, as well as the quality of the correlation between curves, also is provided.

(c) The dipmeter is a good source of information on the location and orientation of primary sedimentary structures over a wide variety of hole conditions. The acoustic televiewer can provide similar information under the proper conditions. The dipmeter also has been advertised widely as a fracture finder; however, it has some of the same limitations as the single-point resistance log when used for this purpose. Computer programs used to derive fracture locations and orientations from dipmeter logs are not as successful as those designed for bedding. Fractures usually are more irregular, with many intersections, and may have a wider range of dip angles within a short depth interval. The acoustic televiewer provides more accurate fracture information under most conditions.

(8) Induction logging.

(a) Principles. Induction-logging devices originally were designed to solve the problem of making resistivity measurements in oil-based drilling mud, where no conductive medium occurred between the tool and the formation. The basic induction-logging system is shown in Figure 7-16. A simple version of an induction probe contains two coils: one for transmitting an AC current, typically 20-40 *Khz*, into the surrounding rocks and a second for receiving the returning signal. The transmitted AC generates a time-varying primary magnetic field which induces a flow of eddy currents in conductive rocks penetrated by the drill hole. These eddy currents set up secondary magnetic fields which induce a voltage in the receiving coil. That signal is amplified and converted to DC before being transmitted up the cable. Magnitude of the received current is proportional to the electrical conductivity of the rocks. Induction logs measure conductivity, which is the reciprocal of resistivity. Additional coils usually are included to focus the current in a manner similar to that used in guard systems. Induction devices provide resistivity measurements regardless of whether the fluid in the well is air, mud, or water, and excellent results are obtained through plastic casing. The measurement of conductivity usually is inverted to provide curves of both resistivity and conductivity. The unit of measurement for conductivity is usually millisiemens per meter (mS/m), but millimhos per meter and micromhos per centimeter are also used. One mS/m is equal to 1,000 Ωm. Calibration is checked by suspending the sonde in air, where the humidity is low, in order to obtain

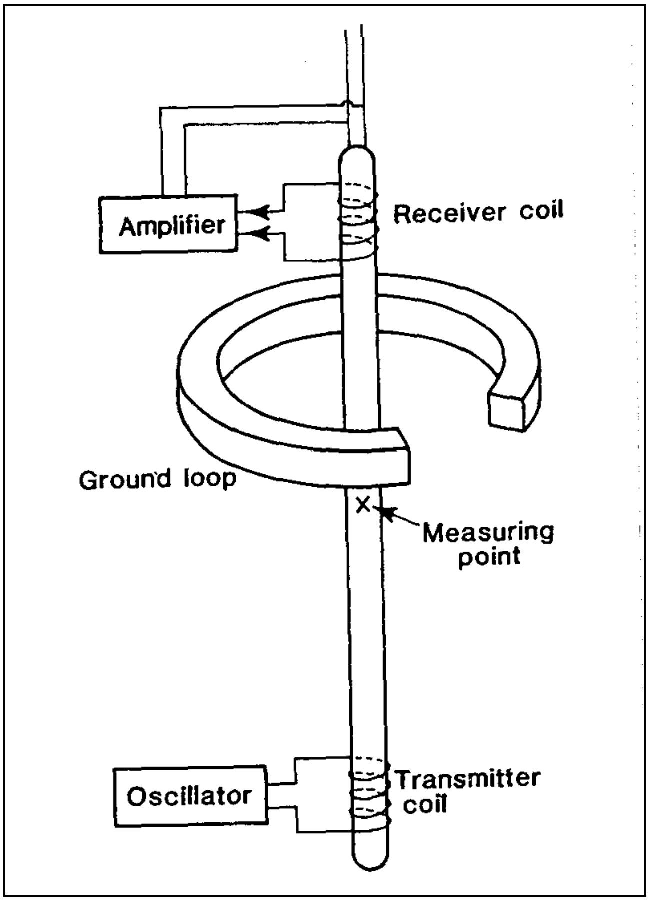


Figure 7-16. System used to make induction logs

a zero conductivity. A copper hoop is suspended around the sonde while it is in the air to simulate known resistivity values. The volume of investigation is a function of coil spacing, which varies among the sondes provided by different service companies. For most tools, the diameter of material investigated is 1.0 to 1.5 *m* (40 to 60 in.); for some tools, the signal produced by material closer to the probe is minimized. Figure 7-17 shows the relative response of a small-diameter, high-frequency, induction tool as a function of distance from the borehole axis. These smaller diameter tools, used for monitoring in the environmental field, can measure resistivities up to 1,000 Ω*m*.

(c) Interpretation and applications. Induction logs are becoming widely used on environmental projects for monitoring saline contaminant plumes by logging small-diameter, PVC- or fiberglass-cased wells. They also provide high-resolution information on lithology through casing and are excellent for this purpose when combined with gamma logs. The response curve in Figure 7-17 is for a tool that can be used in 2-in.-diam casing. Figure 7-18 is a comparison of induction resistivity logs in an open and cased well with a 16-in. normal resistivity log. The open hole was 9 in. and drilled with a mud rotary system. The well was completed to a depth of 56 *m* with 4-in. Schedule 80 PVC casing and neat cement, bentonite seal, and gravel pack. Even in such a large diameter well with varying completion materials, the differences in resistivity are not significant.

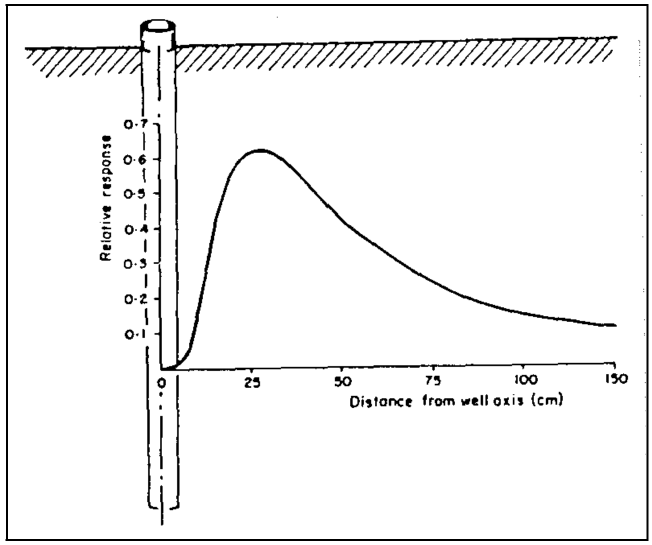


Figure 7-17. Relative response of an induction probe with radial distance from borehole axis (copyright permission granted by Geonics Limited)

(9) Nuclear logging.

(a) Principles. Nuclear logging includes all techniques that either detect the presence of unstable isotopes, or that create such isotopes in the vicinity of a borehole. Nuclear logs are unique because the penetrating capability of the particles and photons permits their detection through casing and annular materials, and they can be used regardless of the type of fluid in the borehole. Nuclear-logging techniques described in this manual include gamma, gamma spectrometry, gamma-gamma, and several different kinds of neutron logs. Radioactivity is measured by converting the particles or photons to electronic pulses, which then can be counted and sorted as a function of their energy. The detection of radiation is based on ionization that is directly or indirectly produced in the medium through which it passes. Three types of detectors presently are used for nuclear logging:

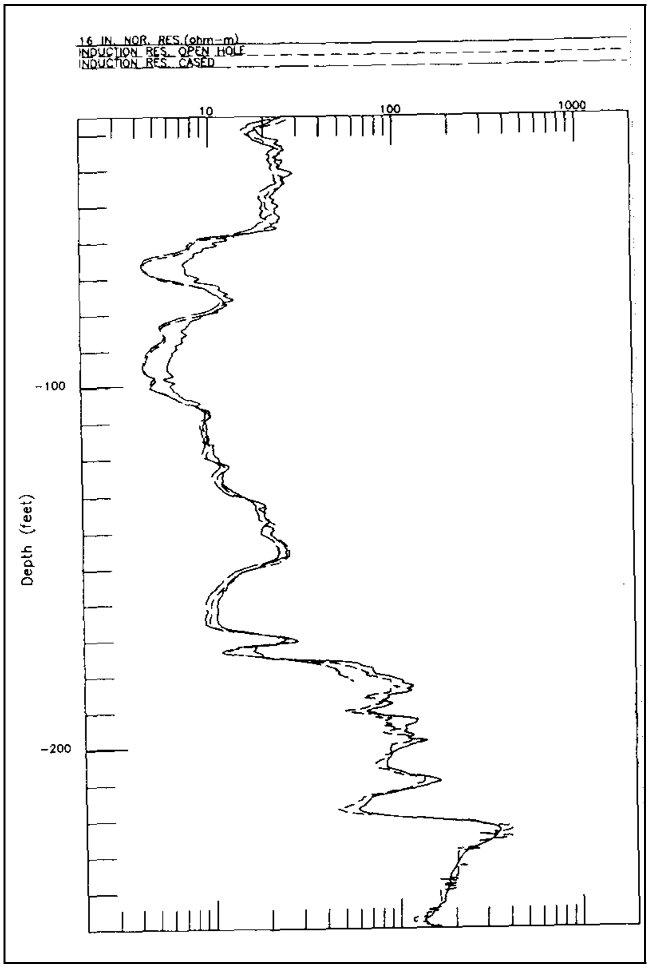


Figure 7-18. Comparison of open-hole induction log with 16-in. normal log and induction log made after casing was installed (copyright permission granted by Colog, Inc.)

scintillation crystals, Geiger-Mueller tubes, and proportional counters. Scintillation detectors are laboratory-grown crystals that produce a flash of light or scintillation when traversed by radiation. The scintillations are amplified in a photomultiplier tube to which the crystal is optically coupled, and the output is a pulse with amplitude proportional to that of the impinging radiation. This output can be used for spectral logging. The pulses output from a photomultiplier tube are small enough that they require additional amplification before they can be transmitted to the surface and counted. The number of pulses detected in a given radiation field is approximately proportional to the volume of the crystal, so probe sensitivity can be varied by changing crystal size. Scintillation crystals probably are the most widely used detectors for nuclear-well logging. Sodium-iodide crystals are used for gamma logging, and lithium-iodide crystals and Helium 3 gas-filled tubes are used for many types of neutron logs.

(b) Interpretation and applications. The statistical nature of radioactive decay must be considered when running or interpreting nuclear logs. Half-life is the amount of time required for one half the atoms in a radioactive source to decay to a lower energy state. Half-life of different radioisotopes varies from fractions of a second to millions of years, and it has been accurately measured. In contrast, it is impossible to predict how many atoms will decay or gamma photons will be emitted within the short periods of time, in the range of seconds, that commonly are used for logging measurements. Photon emission follows a Poisson distribution; the standard deviation is equal to the square root of the number of disintegrations recorded. The accuracy of measurement is greater at high count rates and for a long measuring period. Time constant is an important adjustment on all analog nuclear-recording equipment. Time constant is the time, in seconds, over which the pulses are averaged. Time constant (t_c) is defined as the time for the recorded signal level to rise to 63 percent of the total increase that occurred, or to fall to 37 percent of the total decrease that occurred. The true value in any radiation field is approached after five time constants, if the probe is still in the same bed that long. If the probe is moving too fast, or if the time constant is too long in thin-bedded materials, the true value never will be recorded before the probe moves out of the layer of interest. The logging speed, count rate being measured, vertical resolution required, and equipment variations have a significant effect on the selection of time constant so specific values cannot be recommended.

(c) Analog versus digital recording. The difference between an analog recording with a time constant of 1 sec and a digital recording with a sample time of 1 sec is shown in Figure 7-19. Digital recording is gradually replacing analog but some systems that digitize at the surface still use a time constant circuit to drive an analog recorder. Average or mean radioactivity is shown as the heavier line in Figure 7-19. Note that the digital system changes more rapidly because the time window used does not have a memory like the RC circuit used for time constant in analog measurements. Note also that the analog measurement did not reach the mean value for short time periods. Some commercial logs are recorded at a low sensitivity, long time constant, and high logging speed, so that real changes are small. This results in a smoother curve and thin beds may not be detected. Bed thickness and lag are additional factors related to the

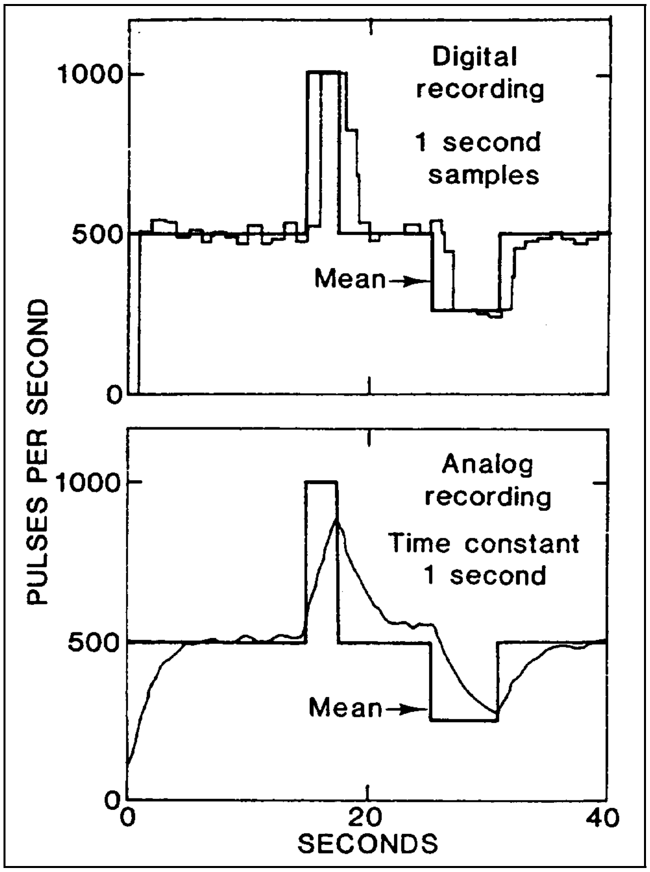


Figure 7-19. Comparison of a digital recording of a gamma signal with 1-s samples, to an analog recording with a 1-s time constant

speed at which nuclear logs are run. Lag (L), in feet, is defined as the distance the detector moves during one time constant:

$$L = (St_c)/60$$

where

S = logging speed, feet per minute

t_c = time constant, seconds

(d) Lithologic contacts. The contacts between lithologic units on a nuclear log are shifted approximately the amount of lag. Furthermore, beds that are thinner than L are not defined. The general practice for locating lithologic contacts on nuclear logs is to place them at one-half of the maximum log amplitude for a given bed. Thus, if the average count rate for a gamma log in a sandstone was 100 pulses per second (PPS), and the average count rate for a shale was 200 PPS, the contact would be placed at 150 PPS, using the half-amplitude rule. The true depth of the contact would be deeper by the amount of lag. See Figure 7-20 for an illustration of the relation of bed thickness, volume of investigation, and location of contacts for a neutron log. The principles are the same for other types of nuclear logs.

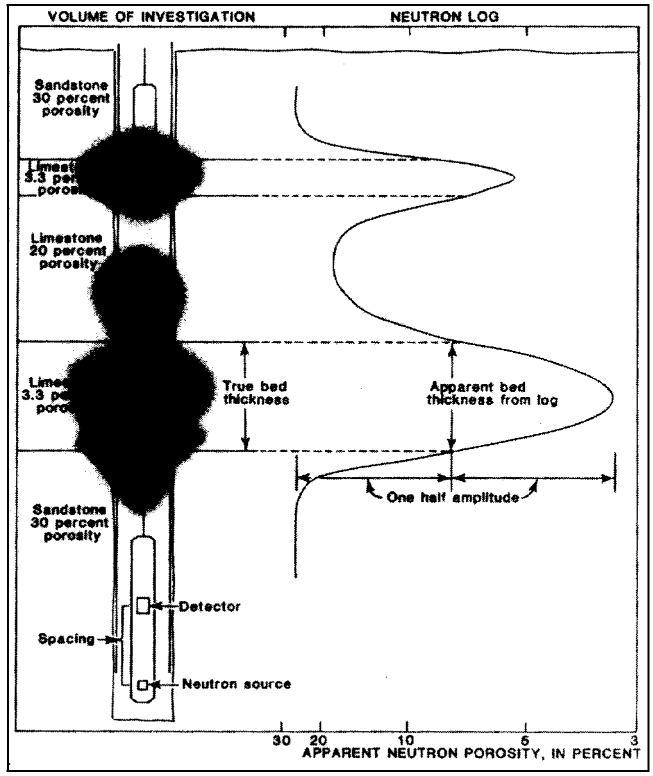


Figure 7-20. Theoretical response of a neutron probe to changes in porosity and bed thickness. The shaded area represents the volume of investigation at different probe positions

(e) Regulation. Use and transportation of radioactive materials is regulated by both Federal and State government agencies. Because of the numerous agencies involved and the frequent changes in regulations, specific information on the subject cannot be provided in this manual. A potential user must consult the appropriate government agency for regulations that apply to the specific type and area of use. The loss of most probes can be prevented if the proper logging procedures are followed. Probes containing radioactive sources need to be the last to be run in an uncased well; they never are run if other probes encounter problems.

(10) Gamma logging.

(a) Principles. Gamma logs, also called gamma-ray logs or natural-gamma logs, are the most widely used nuclear logs for most applications. The most common use is for identification of lithology and stratigraphic correlation, and for this reason gamma detectors are often included in multi-parameter logging tools. Gamma logs provide a record of total gamma radiation detected in a borehole and are useful over a very wide range of borehole conditions. The petroleum industry has adopted the American Petroleum Institute (API) gamma ray unit as the standard for scales on gamma logs. The API gamma-ray unit is defined as 1/200 of the difference in deflection of a gamma log between an interval of very low activity in the calibration pit and the interval that contains the same relative concentrations of radioisotopes as an average shale, but approximately twice the total activity. The API gamma calibration pit is located at the University of Houston. The API values of field standards can be determined when that pit is used so that reference values are available when logging. The volume of material investigated by a gamma probe is related to the energy of the radiation measured, the density of the material through which that radiation must pass, and the design of the probe. Under most conditions, 90 percent of the gamma radiation detected probably originates from material within 150 to 300 mm (6 to 12 in.) of the borehole wall.

(b) Interpretation and applications. In rocks that are not contaminated by artificial radioisotopes, the most significant naturally occurring gamma-emitting radioisotopes are potassium-40 and daughter products of the uranium- and thorium-decay series. If gamma-emitting artificial radioisotopes have been introduced by man into the groundwater system, they will produce part of the radiation measured, but they cannot be identified unless gamma spectral-logging equipment is used. Average concentrations in 200 shale samples from different locations in the United States indicate that 19 percent of the radioactivity of shale comes from Potassium-40, 47 percent from the Uranium series, and 34 percent from the Thorium series, but these ratios can vary significantly. Only gamma spectral logging can provide the identification and relative concentrations of the natural and manmade radioisotopes that produce the total radioactivity measured by a gamma log. Borehole-gamma spectrometry has considerable application to the monitoring of radioactive waste migration and it also can provide more diagnostic information on lithology, particularly the identification of clay minerals. Uranium and thorium are concentrated in clay by the processes of adsorption and ion exchange. Some clays are rich in potassium. Fine-grained detrital sediments that contain abundant clay tend to be more radioactive than quartz sands and carbonates, although numerous exceptions to this norm occur. Rocks can be characterized according to their usual gamma intensity, but knowledge of the local geology is needed to identify the numerous exceptions to the classification shown in Figure 7-21. Coal, limestone, and dolomite usually are less radioactive than shale; however, all these rocks can contain deposits of uranium and can be quite radioactive. Basic igneous rocks usually are less radioactive than silicic igneous rocks, but exceptions are known. Several reasons exist for the considerable variability in the radioactivity of rocks. Uranium and thorium are trace elements and are not important in the genesis of rocks. Uranium also is soluble in groundwater under some conditions; so solution, migration, and precipitation may cause redistribution at any time.

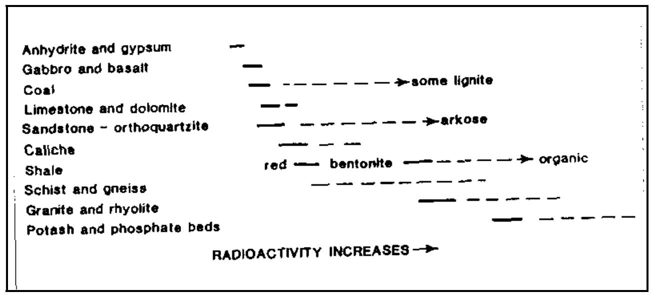


Figure 7-21. Relative radioactivity of some common rocks

(c) Background information. Because of frequent variations from the typical response of gamma logs to lithology, some background information on each new area is needed to reduce the possibility of errors in interpretation. Gamma logs are used for correlation of rock units; however, this approach can lead to significant errors without an understanding of their response within the area being studied. For example, gradual lateral change in grain size or increase in arkosic materials in a sandstone may change the response of gamma logs. In igneous rocks, gamma intensity is greater in the silicic rocks, such as granite, than in basic rocks, such as andesite. Orthoclase and biotite are two minerals that contain radioisotopes in igneous rocks; they can contribute to the radioactivity of sedimentary rocks if chemical decomposition has not been too great. Gamma logs are used widely in the petroleum industry to establish the clay or shale content of reservoir rocks. This application also is valid in groundwater studies where laboratory data support such a relation. Figure 7-2 is a computer-plotted cross section of four test holes in the Chicago area. The shading emphasizes the relation between the induction resistivity and gamma logs which aided in drawing the correlation lines using the computer program. The increase in radioactivity below a depth of 300 ft (91 *m*) is caused by an increase in shale or clay content. Above that depth most of the rocks are dolostones. In this area it was found that gamma log response was quantitatively related to clay content and that the gamma logs could be used to correct porosity calculated from gamma-gamma density logs. See Figure 7-1 for a description of the rocks penetrated by these test holes.

(d) Amplitude. The amplitude of gamma-log deflections is changed by any borehole conditions that alter the density of the material through which the gamma photons must pass or the length of the travel path. Thus, casing and cement will reduce the recorded radiation, as will large diameter wells. The correction factor for water in a borehole as compared to the same borehole filled with air is 1.024 for a 2.25-in.-diam hole and 1.115, 1.205 and 1.296 for 4.5-, 6.5- and 8.5-in. boreholes, respectively. Correction for steel casing wall thickness varies almost linearly from 1.141 for 0.0625 in thickness to 1.891 for 0.375 in thickness. The type of borehole fluid has a very minor effect, unless the hole is very large in diameter or the mud contains radioactive clay or sylvite.

(e) Probe position. The position of a probe in the borehole can have an effect on a gamma log. Most probes are naturally decentralized, or running along the borehole wall, because of borehole deviation but if the probe moves to a centralized position, an error is introduced. Changes in gamma-log response over a period of time are not rare. Changes in gamma response in 1 year, that apparently were caused by migration of uranium daughter products along fractures, have been reported (Keys 1984).

(11) Gamma-gamma logging.

(a) Principles. Gamma-gamma logs, also called density logs, are records of the radiation from a gamma source in the probe, after it is attenuated and backscattered in the borehole and surrounding rocks. The logs can be calibrated in terms of bulk density under the proper conditions and converted to porosity if grain and fluid density are known. Gamma-gamma probes contain a source of gamma radiation, usually cesium-137 in newer probes, and one or two gamma detectors. Detectors in a gamma-gamma probe are shielded from direct radiation from the source by heavy metal, often lead or a tungsten alloy. Single detector probes, termed "4 pi," are not focused and thus are more affected by borehole parameters. Modern gamma-gamma probes are decentralized and side-collimated with two detectors. Side collimation with heavy metal tends to focus the radiation from the source and to limit the detected radiation to that part of the wall of the hole in contact with the source and detectors. The decentralizing caliper arm also provides a log of hole diameter. Modern tools are called borehole-compensated or borehole-corrected, but they still exhibit some borehole diameter effects. The ratio of the count rates for the near and far detectors is plotted against bulk density, either in the logging equipment, or preferably later so that algorithms can be changed (Scott 1977). This ratio reduces borehole diameter effects because the near detector has a smaller radius of investigation than the far detector and is thus more affected by changes in diameter. Gamma-gamma logging is based on the principle that the attenuation of gamma radiation, as it passes through the borehole and surrounding rocks, is related to the electron density of those rocks. If a probe detects only radiation resulting from Compton scattering, the count rate will be inversely proportional to the electron density of the material through which the radiation passes. Electron density is approximately proportional to bulk density for most materials that are logged. A correction for the "Z To A" ratio needs to be applied for any minerals that do not have the same ratio of atomic number to atomic mass as the calibration environment. The electron density of water is 1.11 g/cc versus a bulk density of 1 g/cc and some companies may make this correction. Like other logging systems, calibration of gamma-gamma response is best done in pits designed for that purpose. Calibration can be done in porosity pits like the American Petroleum Institute neutron pit in Houston or in pits maintained by commercial-service companies. A set of bulk-density pits is available for free use by anyone at the Denver Federal Center. Onsite standardization of probe response usually is done with large blocks of aluminum, magnesium, or lucite that are machined with a groove that tightly fits the source and detector section of the probe. The blocks need to be large enough that effects of the environment are minimized, and they need to be located off the ground and away from a logging truck that may contain radioactive sources.

(b) Volume of investigation. The volume of investigation of a gamma-gamma probe probably has an average radius of 127 to 152 mm (5 to 6 in.); 90 percent of the pulses recorded originate from within this distance. However, the volume of investigation is a function of many factors. The density of the material being logged and any casing, cement, or mud through which the radiation must pass have a significant effect on the distance gamma photons will travel before being stopped. Within limits, the greater the spacing between source and detector, the larger the volume of investigation. Standoff error is caused when a side-collimated, decentralized probe or skid is separated from the borehole wall by mudcake or wall roughness. According to Scott (1977), standoff errors of 10 mm (0.4 in.) or more may be corrected accurately using the algorithms he developed.

(c) Interpretation and applications. Gamma-gamma logs may be used to distinguish lithologic units and to determine well construction, in addition to determining bulk density, porosity, and moisture content, when properly calibrated. The chief use of gamma-gamma logs has been for determining bulk density that can be converted to porosity. Gamma-gamma logs conventionally are recorded with bulk density increasing to the right, which means that porosity increases to the left as it does on conventionally plotted neutron and acoustic velocity logs. Although commercial gamma-gamma logs often have a scale in porosity, the log response is related directly to electron density, which may be related to bulk density by calibration and correction for Z-A errors. The accuracy of bulk-density determinations with these logs is reported by various authors to be from 0.03 to 0.05 g/cc. Figure 7-22 is a plot of bulk density from laboratory analyses of core versus density log values from a study in Canada (Hoffman, Fenton, and Pawlowica 1991). It shows how accurate density logs can be under the right conditions. The best results are obtained with gamma-gamma logs in rocks of low-bulk density or high porosity. Bulk density can be converted to porosity by the following equation: porosity = grain density minus bulk density divided by grain density minus fluid density. Bulk density may be derived from a calibrated and corrected log.

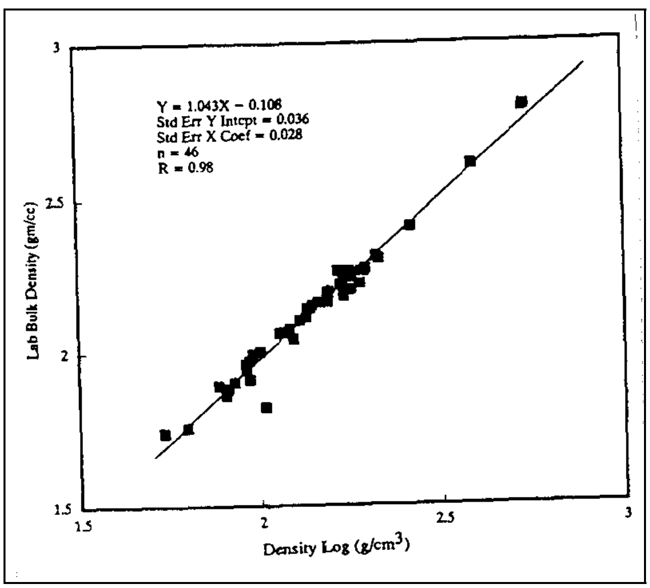


Figure 7-22. Plot of laboratory measurements of bulk density versus gamma-gamma density log response in the same borehole (Hoffman, Fenton, and Pawlowicz 1991; copyright permission granted by Alberta Research Council)

Fluid density is 1 g/cc for most non-petroleum applications, where the rock is saturated. Grain or mineral density may be obtained from most mineralogy texts; grain density is 2.65 g/cc for quartz; 2.71 g/cc commonly is used for limestone, and 2.87 g/cc commonly is used for dolomite. At the Chicago site shown in Figures 7-1 and 8-3, gamma log response was used to correct the grain density entered in the porosity equation. Low gamma response indicated mostly dolomite, and higher gamma response indicated an increase in clay with a lower grain density than dolomite. At many sites gamma-gamma logs provide more accurate porosity data than neutron and acoustic velocity logs. Figure 7-23 is an example of a comparison of data from the three types of porosity sensing logs versus core data at a Superfund site in Oklahoma (Keys 1993). Because moisture content affects the bulk density of rocks, gamma-gamma logs can be used to record changes in moisture above the water surface. Thus they can be used in the same way as neutron logs to monitor the downward migration of water from waste disposal or artificial recharge ponds.

(d) Well construction. The effect of well construction on gamma-gamma logs can be used to locate cement tops, gravel-pack fill-up, or one string of casing outside of another. Gamma-gamma logs for this application are discussed in the section of this manual on well-completion logs.

(12) Neutron logging.

(a) Principles. Neutron logs are made with a source of neutrons in the probe and detectors that provide a record of the interactions that occur in the vicinity of the borehole. Most of these neutron interactions are related to the amount of hydrogen present, which, in groundwater environments, is largely a function of the water content of the rocks penetrated by the drill hole. Neutron probes contain a source that emits high-energy neutrons. The most common neutron source used in porosity logging tools is americium-beryllium, in sizes that range from approximately 1 to 25 Curies. Moisture tools may use a source as small as 100 millicuries. Two different neutron-logging techniques are used in groundwater studies: Neutron probes with a large source and long spacing are used for measuring saturated porosity and moisture content in a wide range of borehole diameters; and second, probes with a small source and short spacing are used for measuring moisture content in small diameter monitoring wells. Three general types of neutron-porosity logs exist: Neutron-epithermal neutron, neutron-thermal neutron, and neutron-gamma. Cadmium foil may be used

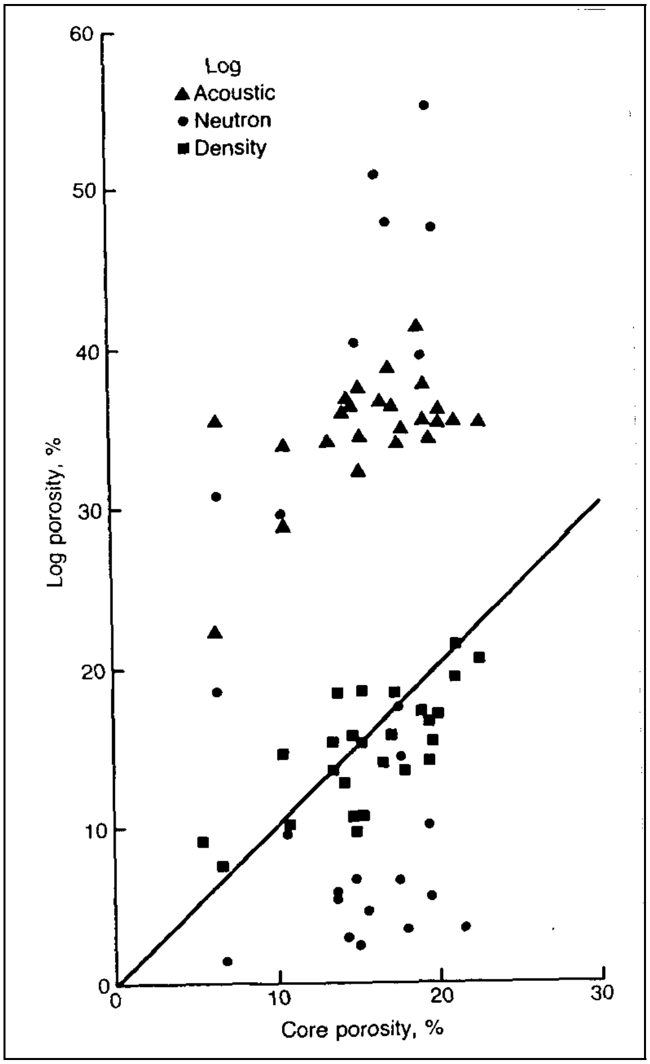


Figure 7-23. Comparison of laboratory measurements of porosity versus acoustic, neutron, and density log response in the same borehole

to shield crystal or Helium-3 detectors from thermal neutrons. Neutron- epithermal neutron logs are least affected by the chemical composition of the rocks logged. Two or more detectors are used in modern neutron tools, and they may be collimated and decentralized by a caliper arm. The ratio of the near to the far detector provides logs that are less affected by borehole parameters than single-detector logs.

(b) Moderating neutrons. Fast neutrons, emitted by a source, undergo three basic types of reactions with matter in and adjacent to the borehole as they lose energy and ultimately are captured: inelastic scatter, elastic scatter, and absorption or capture. In elastic scatter, the mass of the scattering element controls the loss of energy by the neutron. Light elements are most effective in moderating, or slowing neutrons, whereas heavy elements have little effect on neutron velocity or energy. Hydrogen is the element most effective in moderating neutrons because it has the same mass as a neutron. Because hydrogen is the most effective moderating element, the cloud of epithermal and thermal neutrons occurs closer to the source in rocks with a large hydrogen content than in rocks with a small hydrogen or water content. The moderating and capture processes result in the number of epithermal and thermal neutrons and capture gamma photons being inversely related to the hydrogen content of the rocks, at source-to-detector spacing greater than approximately 300 mm (11.8 in.). If detectors are located closer than 300 mm from the source, as in moisture probes, the number of moderated and captured neutrons increases with increasing hydrogen content.

(c) Volume of investigation. The volume of investigation of a neutron probe is related closely to the content of hydrogen or other strong neutron absorbers in the material surrounding the probe, the spacing between the source and detector, and the energy of the neutrons. In sand with a saturated porosity of 35 percent, three different types of neutron probes received 90 percent of the recorded signal within 170, 236, and 262 mm of the borehole wall. In dry rocks the radius of investigation may be several meters. The reference depth, or point of measurement, on a probe may change somewhat if significant differences in water content are logged. Increasing the source-to-detector spacing increases the volume of investigation in the vertical direction as well as in the horizontal direction, into the rock. This increased volume decreases thin-bed resolution as demonstrated in Figure 7-20. The hypothetical volume of investigation is shown by shading in the figure. Note that size and shape of this volume are shown to change as a function of the porosity as the probe moves up the hole. The log only gives an approximately correct value for porosity and thickness when the volume of investigation is entirely within the bed being logged. Thus, in Figure 7-20, the upper thin limestone bed with 3.3 percent porosity is indicated by the log to have a much higher porosity and greater apparent thickness than the lower bed with a porosity of 3.3 percent. The usual technique for determining bed thickness from any type of nuclear log is to make the measurement at one-half the maximum amplitude of the deflection that represents that bed, as shown on the figure.

(d) Calibration. Calibration of all neutron-logging systems used in the petroleum industry is based on the API calibration pit in Houston, Texas. The pit contains quarried limestone blocks that have average porosities of

1.884, 19.23, and 26.63 percent. These values have been rounded by the American Petroleum Institute to 1.9, 19, and 26 percent, and the 19-percent block has been assigned the value of 1,000 API neutron units (Belknap et al. 1959). Figure 7-24 shows calibration data for a compensated neutron probe in the API pit (Keys 1990). Although the API pit is the widely accepted primary standard, it is only valid for limestone, so that most large logging companies maintain their own calibration facilities for other rock types, like dolomite and sandstone. Careful evaluation of laboratory analyses of core samples may lead to a valid calibration, but scatter of data points is to be expected. Regardless of how primary calibration is carried out, field standardization must be done at the time of calibration and frequently during logging operations. The most practical field standards permit the checking of probe response with the source installed in a reproducible environment that has a high hydrogen content. Although a plastic sleeve may be used, it must be quite heavy to be large enough to cover both source and detectors and thick enough to reduce outside effects.

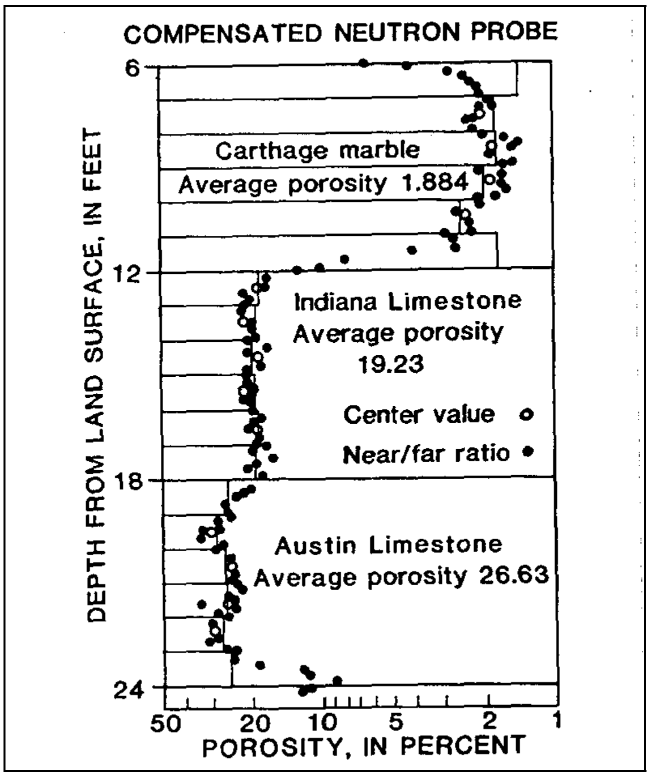


Figure 7-24. Calibration data for a compensated neutron-porosity probe in the API limestone pit

(e) Interpretation. In many rocks, the hydrogen content is related to the amount of water in the pore spaces. This relation is affected by the chemical composition of the water, hydrogen in some minerals and bound water in shales. Neutron logs are affected by many of the same borehole parameters that affect gamma-gamma logs, although usually to a lesser degree. These extraneous effects include borehole diameter, mud cake or stand off, salinity of the borehole and interstitial fluids, mud weight, thickness of casing and cement, temperature and pressure, and elemental composition of the rock matrix. Matrix effects are considered part of the interpretation process and may be analyzed by cross-plotting techniques, as illustrated in Figure 7-3. Casing does not cause a major shift on most neutron logs, as it typically does on a gamma-gamma log. Neutron logs run through drill stem do not show the location of collars as a gamma-gamma log does. Plastic pipe of constant thickness merely causes a shift in log response similar to, but of lower magnitude than, that caused by the water level in a small-diameter well. The short spacing used in moisture probes reduces the volume of investigation, so that borehole effects are increased. For this reason, boreholes to be used for logging with a moisture probe need to be drilled as small as possible. The annular space between casing and borehole wall also needs to be small, and the probe needs to fit the casing tightly. Neutron logs are most suitable for detecting small changes in porosity at low porosities; gamma-gamma logs are more sensitive to small changes at high porosities. Although the interpretation of neutron logs for porosity and moisture content are stressed as primary applications, much use has been made of the logs for determining lithology. Like gamma logs, they can be used for lithology and stratigraphic correlation over a wide range of borehole conditions. Figure 7-1 shows how neutron and gamma logs relate to the stratigraphic units in a test hole near Chicago.

(f) Applications. Neutron-activation logging has potential for application to groundwater quality problems, because this technique permits the remote identification of elements present in the borehole and adjacent rocks under a wide variety of borehole conditions. Neutron activation produces radioisotopes from stable isotopes; the parent or stable isotope may be identified by the energy of the gamma radiation emitted and its half-life, using a gamma spectral probe (Keys and Boulogne 1969).

(13) Acoustic logging. Acoustic logging includes those techniques that use a transducer to transmit an acoustic wave through the fluid in the well and surrounding elastic materials. Several different types of acoustic logs are used, based on the frequencies used, the way the signal is recorded, and the purpose of the log. All these logs require fluid in the well to couple the signal to the surrounding rocks. Four types will be described here:

acoustic velocity, acoustic wave form, cement bond, and acoustic televiewer.

(14) Acoustic-velocity logging.

(a) Principles. Acoustic-velocity logs, also called sonic logs or transit-time logs, are a record of the travel time of an acoustic wave from one or more transmitters to receivers in the probe. Acoustic energy travels through the fluid in the well and through surrounding materials at a velocity that is related to the lithology and porosity of the rocks. Most acoustic-velocity probes employ magnetorestrictive or piezoelectric transducers that convert electrical energy to acoustic energy. Most of the transducers are pulsed from 2 to 10 or more times per second, and the acoustic energy emitted has a frequency in the range of 20 to 35 kHz. Probes are constructed of low-velocity materials, producing the shortest travel path for the acoustic pulse through the borehole fluid and the adjacent rocks, which have a velocity faster than that of the fluid. Acoustic probes are centralized with bow springs or rubber fingers so the travel path to and from the rock will be of consistent length. Some of the energy moving through the rock is refracted back to the receivers. The receivers reconvert the acoustic energy to an electrical signal, which is transmitted up the cable. At the surface, the entire signal may be recorded digitally for acoustic wave-form logging, or the transit time between two receivers may be recorded for velocity logging. Amplitude of portions of the acoustic wave also may be recorded; that technique is described later under wave-form logging.

(b) Acoustic energy components. Acoustic energy transmitted in the borehole and adjacent rocks is divided into several components; the most important for this discussion are compressional (P) and shear wave (S) components. Standard acoustic-velocity logs are based on the arrival of the compressional wave. Compressional and shear waves at near and far receivers, along with the fluid waves that are transmitted through the borehole, are shown in Figure 7-25 (Paillet and White 1982). Most acoustic-velocity probes have paired receivers located a foot apart; some probes have several pairs of receivers with different spacing that may be selected from the surface. P-waves have a higher velocity and lower amplitude than shear waves, or S-waves. S-waves have a velocity about one half that of P-waves and are characterized by particle movement perpendicular to the direction of wave propagation.

(c) Tracking circuits. Acoustic-velocity logging modules contain a tracking circuit that detects the arrival

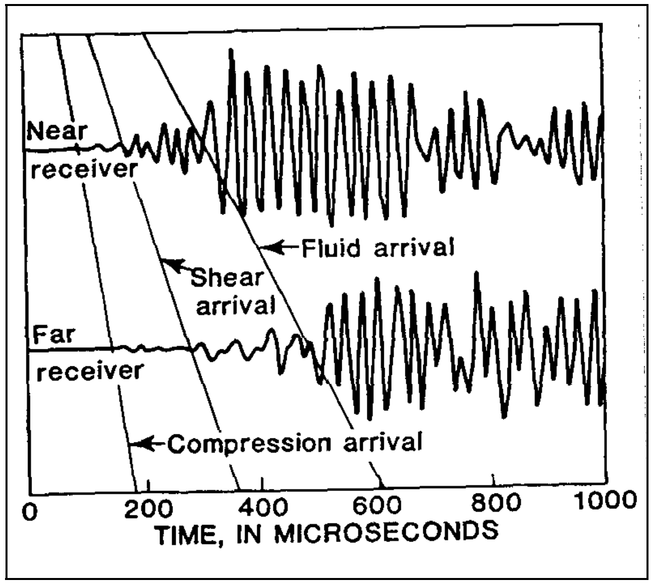


Figure 7-25. Acoustic wave forms for a two-receiver system

of the P-wave using a threshold amplitude or algorithm selected by the operator. If the wave form is digitized in the field it is frequently possible to improve acoustic velocity logs by modifying the technique used to pick the first arrival. Amplitude of the transmitted signal and the received signal may be controlled from the surface, along with the height of the detection threshold. A circuit is employed to convert the difference in time of arrival at the two detectors to transit time (t) in µs/ft. Acoustic-velocity logs are recorded with interval transit time increasing from right to left; porosity also will increase to the left, as it does on conventionally plotted neutron and gamma-gamma logs.

(d) Interpretation and applications. For rocks with uniformly distributed, intergranular pore spaces, porosity usually is derived from the Wyllie time-average equation. This equation is based on the theory that the path of an acoustic wave through saturated rock consists of two velocities in series, the velocity in the fluid V_f and the velocity in the rock matrix V_m. The length of the path in the fluid is equal to the porosity (ϕ); the length of the path in the rock matrix is equal to 1-ϕ. The time-average equation can be expressed as:

$$1/V_L = t = \phi/V_f + (1 - \phi)/V_m$$

where

V_L = velocity of the rock from a log

For calculation of porosity, the time-average equation is converted to the form:

$$\phi = (t_L - t_m)/(t_f - t_m) \qquad (7\text{-}3)$$

where

t_L = transit time from the log

t_m = transit time of the wave in the matrix

t_f = transit time in the fluid

Velocities and transit times for some common rocks and fluids are provided in Table 7-2. Note that the range can be very large, so laboratory measurements or background experience in specific rocks may be needed to calculate accurate porosities. The interval transit-time scale usually is accurate within 1 µs/ft on most acoustic-velocity logs; however, it should be checked, if possible. The difference in arrival of the P-wave at two receivers can be read directly from a calibrated oscilloscope, which is an essential part of any acoustic-logging system unless the wave form is digitized in the tool. In this case a computer can be used to observe the wave forms. Calibration also can be accomplished using core samples analyzed in the laboratory for acoustic velocity and porosity. The response of a velocity probe can be checked onsite with a piece of steel pipe cut in half lengthwise. The tool can be laid in the pipe and dams made at both ends with flexible caulking, so that half of the transmitters and receivers can be covered with water. Steel has a velocity ranging from 17,000 to 20,000 ft/s, which can be used to check the calibration of the sonde. It is possible to make the same check in a drill hole that contains free-hanging steel pipe.

Table 7-2
Compressional-Wave Velocity and Transit Time in Some Common Rocks and Fluids [Single values are averages]

Rock or Fluid Type	Velocity (m/s)	(ft/s)	Transit time (µs/ft)
Fresh water	1,500	5,000	200.0
Brine	1,600	5,300	189.0
Sandstone			
Unconsolidated	4,600-5,200	15,000-17,000	58.8-66.7
Consolidated	5,800	19,000	52.6
Shale	1,800-4,900	6,000-16,000	62.5-167.0
Limestone	5,800-6,400	19,000-21,000+	47.6-52.6
Dolomite	6,400-7,300	21,000-24,000	42.0-47.6
Anhydrite	6,100	20,000	50.0
Granite	5,800-6,100	19,000-20,000	50.0-52.5
Gabbro	7,200	23,600	42.4

(e) Radius of investigation. The radius of investigation of an acoustic-velocity probe is reported to be approximately three times the wavelength (Pirson 1963). The wavelength is equal to the velocity divided by the frequency. At a frequency of 20,000 Hz, the radius of investigation theoretically is about 0.23 m (0.75 ft) for unconsolidated rocks with a velocity of 1,500 m/s (5,000 ft/s), and 1.1 m (3.65 ft) for very hard rocks with a velocity of 7,600 m/s (25,000 ft/s). A lower transmitter frequency will increase the volume of investigation, but it will decrease the resolution of small features, such as fractures.

(f) Cycle skipping. One of the most obvious problems on acoustic-velocity logs is cycle skipping, caused by the amplitude of the first compressional cycle being too low for detection, or by pre-arrival noise of sufficient amplitude to be detected. If the first cycle is detected at the near receiver and the second cycle is detected at the far receiver, the resulting transit time will be much too long, and the log will show a very sharp deflection. Often signal amplitude will vary above and below detection level, which causes rapid fluctuations in the log trace, which can be recognized as cycle skips. Cycle skipping frequently is blamed on gas in the well; however, any condition that causes the compressional wave to drop below detection level will produce cycle skipping on the log. Causes include improper adjustment of signal or detection level, fractures or washouts, high-attenuation rocks, and gas in the fluid. Cycle skipping can be used to locate fractures in some wells, but corroborating evidence is necessary.

(g) Lithologic factors. Acoustic velocity in porous media is dependent on such lithologic factors as: the type of matrix; density; size, distribution, and type of grains and pore spaces; degree of cementation; and the elastic properties of the interstitial fluids. The widely used time average equation does not account for most of these factors, but it has been found to produce reasonably correct porosity values under most conditions. Figure 7-26 is a plot of porosity values measured on core versus transit time from an acoustic-velocity log, for a sequence of basin-fill sedimentary and volcanic rocks in Idaho. The correlation coefficient for the core and log data from this well is 0.87, even though a wide range of rock types with different matrix velocities were logged. Acoustic-velocity logs are very useful for providing information on

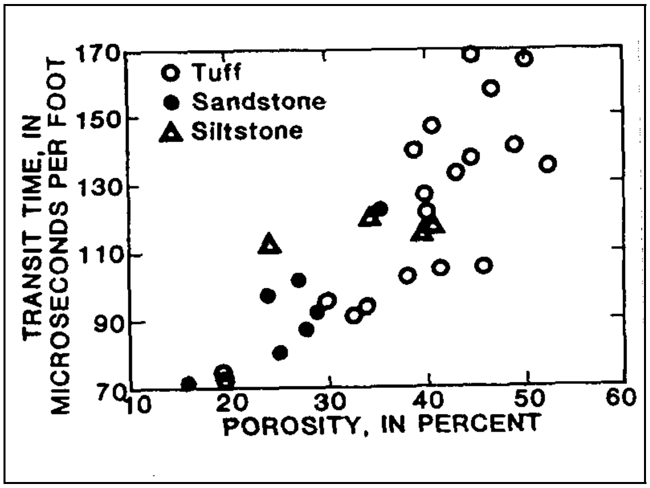


Figure 7-26. Relation of acoustic-transit time to porosity for tuff, sandstone, and siltstone, Raft River geothermal reservoir, Idaho

lithology and porosity under a fairly wide range of conditions. They usually are limited to consolidated materials penetrated by uncased, fluid-filled wells; however, lithologic information can be obtained when casing is well bonded to the rocks. Resolution of thin beds is good when 1-ft receiver spacing is used; contacts usually are marked by sharp deflections.

(h) Secondary porosity. In some geohydrologic environments, such as carbonates, porosity from an acoustic-velocity log and from a neutron log or core can be cross-plotted to identify intervals of secondary porosity. Acoustic-velocity logs do not detect most nonuniformly distributed secondary porosity, whereas neutron logs respond to all water-filled pore spaces. This is demonstrated in Figure 7-3, computer-generated cross plot of the neutron log versus acoustic-velocity log for Madison limestone test well No. 1 (Keys 1986). In the permeable intervals identified on flowmeter logs, many acoustic-log porosities were lower than the corresponding neutron-log and core values because of secondary porosity (Figure 7-3).

(15) Acoustic wave-form logging.

(a) Principles. Considerable information on lithology and structure is available through analyses of the various components of a received acoustic signal. Analyses may include amplitude changes, ratios of the velocities of various components of the wave train, and frequency-dependent effects. Hearst and Nelson (1985) present a broad discussion on acoustic logging and the propagation of waves in geologic media. There are two main categories of waves in a borehole: (a) refracted waves, and (b) guided waves. Refracted waves travel from the transmitter through the fluid and are refracted at the borehole wall, where they travel through the rock until refracted again through the fluid to the receivers. Guided waves travel in the borehole fluid or at the borehole wall/fluid interface. Cement-bond logs are included in this section, because wave-form data are needed to increase the accuracy of interpretation of these logs. Acoustic wave forms can be recorded digitally, pictures can be made of the display on an oscilloscope, or a variable-density log can be made. The variable-density log (VDL) or 3-dimensional (3-D) velocity log is recorded photographically, so that variations in darkness of the record are related to changes in amplitude of cycles in the wave form. Figure 7-27 includes a VDL display. The banded display on the right is the VDL, which is a representation of the wave train in time from transmitter pulse. Frequency of the waves is related to the width of the black and white or grey bands. The grey scale scheme in this VDL is such that white represents high-amplitude negative wave pulses, grey the low-amplitude waves, and black represents high-amplitude positive pulses. A digitized wave form log is the most useful type of record, because data can be analyzed quantitatively. Velocities and amplitudes of all parts of the recorded wave form can be measured from a digital record. Furthermore, digitized wave form data enable acoustic velocity or transit time logs to be corrected later where the algorithm that detected the first arrival was not functioning properly.

(b) Interpretation and applications. Elastic properties of rocks can be calculated from the velocities of P- and S-waves and from corrected bulk density from a gamma-gamma log. [Also see the discussion in paragraph 3-1*a*(1)(d).] The elastic properties or constants that can be determined are shear modulus, Poisson’s ratio, Young’s modulus, and bulk modulus (Yearsley and Crowder 1990). The shear modulus is defined in terms of density and S-wave velocity, as given in the following equation:

$$G = p_b V_s^2 \qquad (7\text{-}4)$$

where

G = shear modulus

p_b = bulk, mass density

V_s = shear-wave velocity

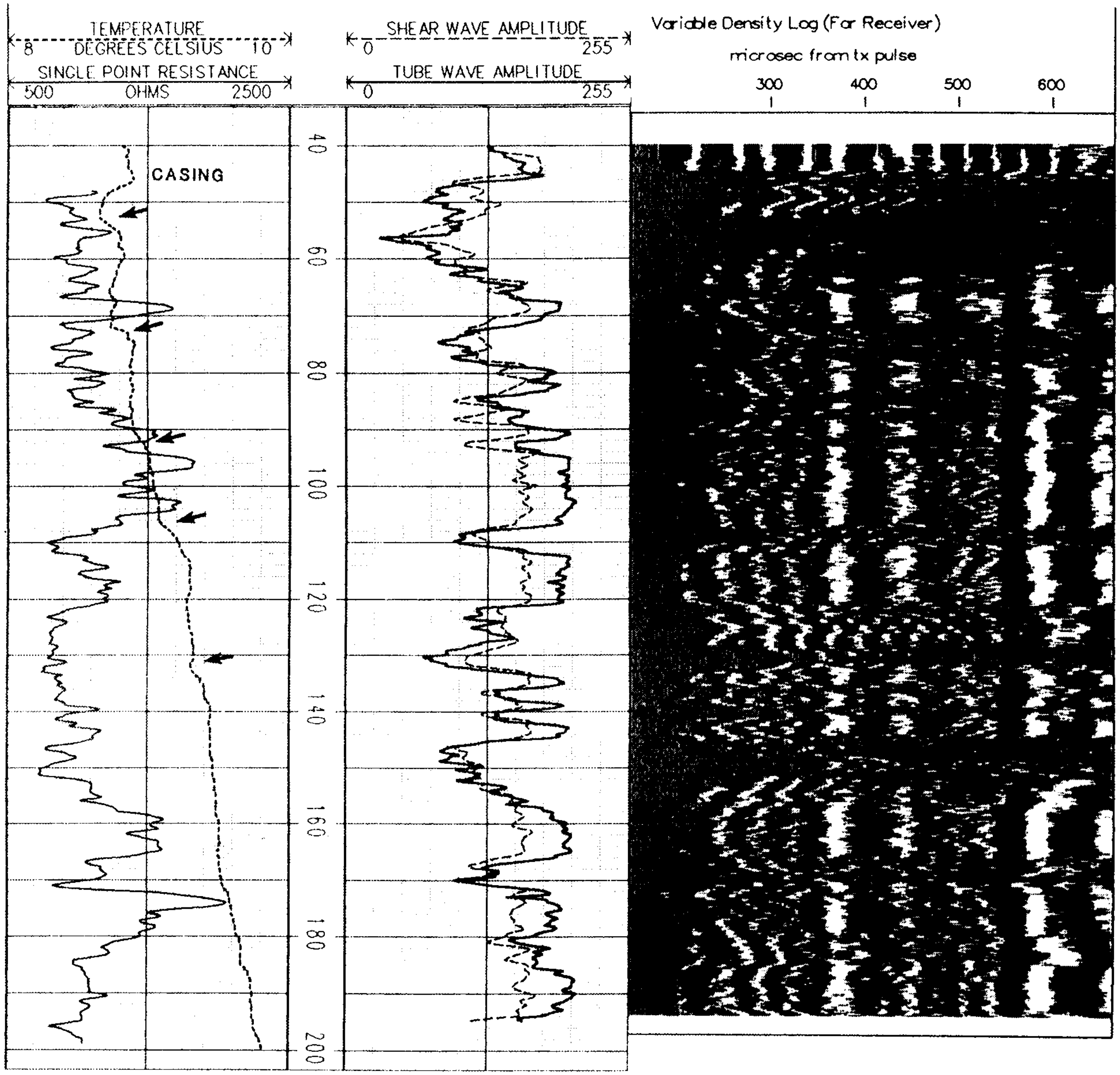


Figure 7-27. Composite of logs showing the location of permeable fractures indicated by the arrows at changes in temperature gradient and by low tube and shear wave amplitude (Yearsley and Crowder 1990; copyright permission granted by Colog, Inc.)

Poisson's ratio ν is the ratio between strain in the direction of principal stress and strain in either transverse direction, and is defined in terms of P- and S-wave velocities by the following [also Equation 3-1]:

$$\nu = (a^2 - 2)/[2(a^2 - 1)] \tag{7-5}$$

where

ν = Poisson's ratio

$a = V_p/V_s$

V_p = P-wave velocity

Young's modulus is the factor of proportionality between stress and strain and is fundamentally related to the material constants given above by the following equation:

$$E = 2G(1 + \nu) \tag{7-6}$$

where

E = Young's modulus

It should be noted that the above relationships were derived for homogeneous, isotropic conditions, which do not exist in the geologic environment. Still, in practice these expressions provide useful engineering estimates for the elastic properties of rocks, and an analytical overview of the interrelationships among density, velocity, and moduli. For example, Equation 7-4 reveals that the shear modulus varies directly with density, but with the square of shear velocity, indicating the strong dependency of the shear modulus on transverse velocity. It is interesting to note from Equation 7-5 that Poisson's ratio is not physically meaningful for compression/shear velocity (V_p/V_s) ratios less than 1.42 (Poisson's ratio becomes negative). In general, higher Poisson's ratios indicate less competent rock. Ice, which is more deformable than most rock, has a V_p/V_s ratio of approximately 2.0, which corresponds to a Poisson's ratio of 0.33. The result of this type of analysis is the engineering properties log shown in Figure 7-28. Competent rock below 44 m stands out clearly in Figure 7-28 with moduli of nearly twice the weathered rock and five times the fractured rock. However, note the minor fracture zones in evidence in the competent rock mass, indicated by excursions to the left on both the moduli curves and velocity curve. The major fracture zones in the overlying rock are shown by extremely low shear moduli of less than 14 gigapascals (two million psi). The core-derived rock quality determination plotted in Figure 7-28 grossly indicates the difference between the competent rock mass and the overlying weathered and fractured rock in this core hole.

(c) Tube waves. Paillet (1980 and 1981) describes the characterization of fractures by various acoustic techniques. A significant finding was that a semiquantitative correlation exists between the attenuation of tube-wave amplitude in small-diameter drill holes in crystalline rocks and the permeability of fractures determined by packer-isolation tests. Thus, tube-wave amplitude logging has the potential for predicting the relative flow through fractures in hard rocks. The tube wave is part of the fluid wave propagated along the borehole wall under certain conditions; it apparently is attenuated where water in the borehole is free to move in and out of fractures. Figure 7-29 shows the correlation between a tube wave amplitude log calculated from digitized acoustic wave form data and fracture aperture or permeability from straddle packer tests (Davison, Keys, and Paillet 1982). Figure 7-27 is a composite log including shear and tube wave amplitude, temperature, single point resistance, and VDL. VDL indicates fractures as the low-velocity zones. The single point resistance is primarily controlled by the presence or absence of fractures. Natural flow in or out of the borehole through fractures affects the thermal gradient of the borehole fluid so that changes noted on the temperature log by arrows indicate natural fracture flow. The amplitude logs in Figure 7-27 were computed by calculating the root mean square amplitude within specified time windows. Two additional fracture zones evident on the VDL, and as low-amplitude excursions on the amplitude logs at 146-148 and 170 ft (44.5-45 and 52 m), are not obvious on the temperature log.

(16) Cement-bond logging. Cement-bond logging usually employs a single receiver to obtain information on the quality of the bond between casing and cement and between cement and borehole wall. Most cement-bond logs are a measurement only of the amplitude of the early arriving casing signal, but to improve the accuracy of interpretation, the full acoustic wave form is needed for study. Although a small amount of the total acoustic energy may be received from the rock when the casing is free to vibrate, the formation signal usually is not detectable. The detection of channeling through cement in the annular space is one of the main objectives of cement-bond logging; yet, even an expert in the analysis of cement-bond logs probably will not locate all channels accurately.

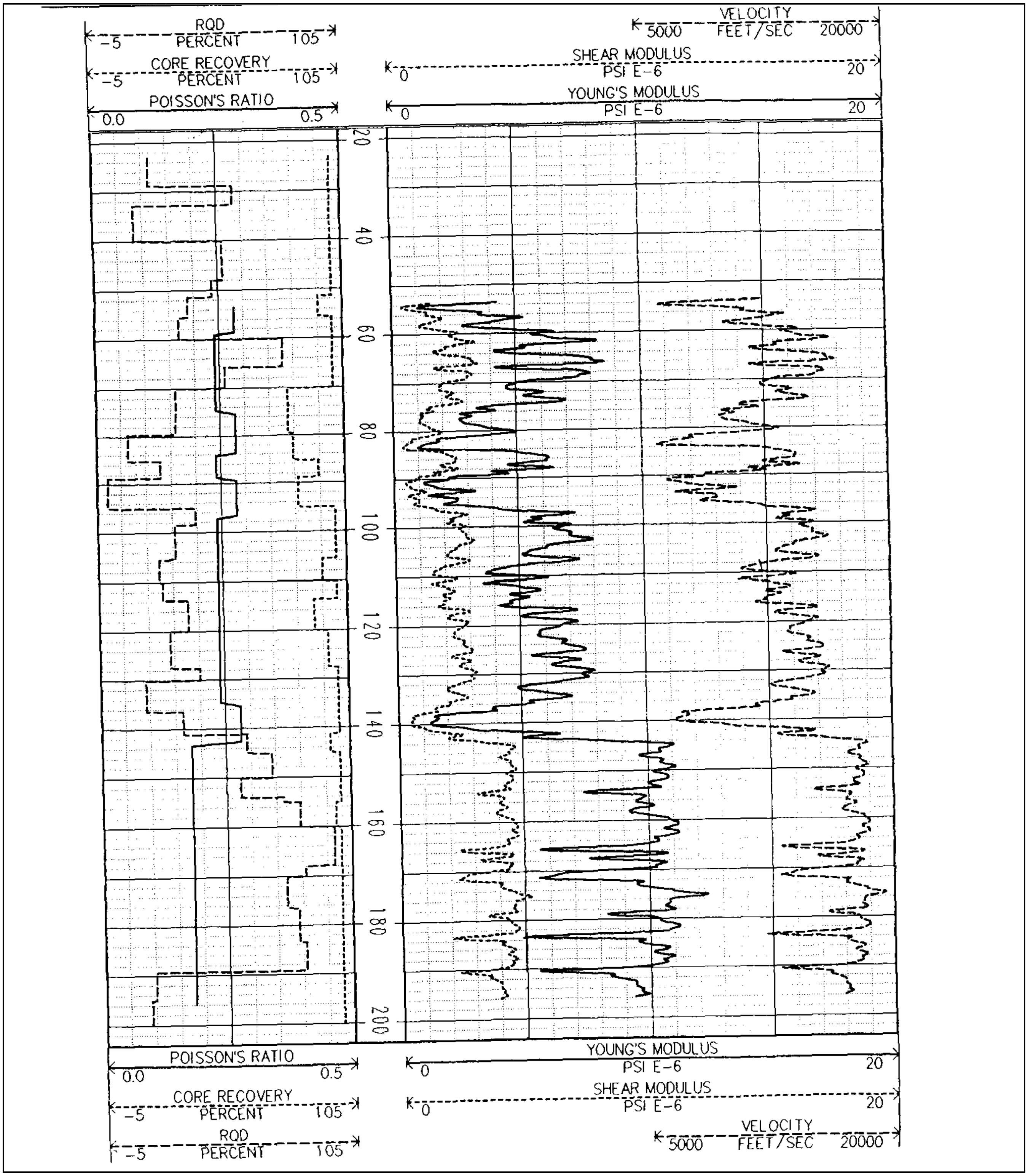


Figure 7-28. Engineering properties calculated from geophysical logs of a core hole compared with rock quality determination (RQD) from the core (Yearsley and Crowder 1990; copyright permission granted by Colog, Inc.)

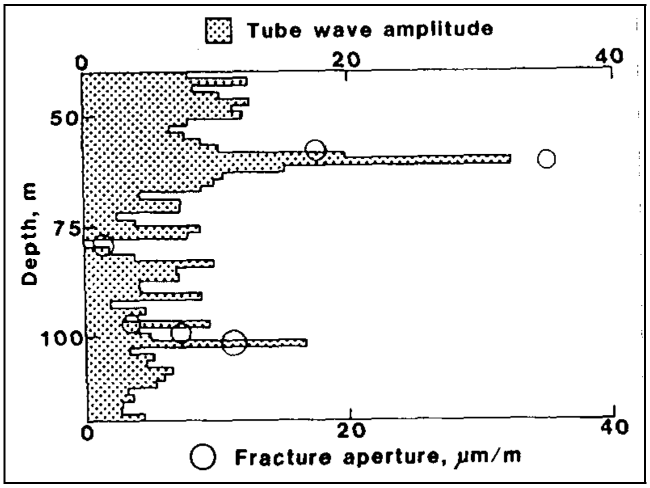


Figure 7-29. Plot showing a comparison of tube wave amplitude calculated from acoustic wave form data and hydraulic fracture aperture calculated from straddle packer tests

(17) Acoustic-televiewer logging.

(a) Principles. An acoustic televiewer (ATV) is a logging device that can provide high-resolution information on the location and character of secondary porosity, such as fractures and solution openings. It also can provide the strike and dip of planar features, such as fractures and bedding planes. An ATV also is called the borehole televiewer but this term occasionally causes it to be confused with borehole television. An ATV employs a rotating high-frequency transducer that functions as both transmitter and receiver (Zemanek et al. 1969). The piezoelectric transducer is rotated at three or more revolutions per second and is pulsed approximately 1,200 times per second. High-frequency acoustic energy is reflected from, but does not penetrate, the borehole wall. A trigger pulse is transmitted to the surface equipment from a fluxgate magnetometer each time the transducer rotates past magnetic north. This pulse triggers the sweep of an oscilloscope or graphic recorder, so that each sweep represents a 360-deg scan of the borehole wall. The brightness of the oscilloscope trace is proportional to the amplitude of the reflected acoustic signal, somewhat analogous to a rotating depth finder in a boat.

(b) Procedure. The probe must be centralized accurately with bow springs, so the signal path will be the same length in all directions. As the probe moves up the hole, a signal is generated that moves the sweeps across the oscilloscope or other type of graphic recorder to produce a continuous record of the acoustic reflectivity of the borehole wall. The received signal may also be recorded in analog format on standard VHS tape for later playback and enhancement of the graphic record. The signal from the ATV probe may be digitized in new generation probes or subsequently from the VHS analog tape from older systems. The digital data file may then be enhanced, analyzed, and displayed in various color formats using a computer program. This program, and similar programs developed by logging companies, produces three-dimensional plots, calculates the aperture and strike and dip of fractures, the orientation of breakouts, borehole diameter, acoustic reflectivity, stress field, etc. The ATV log is a cylinder that has been opened along the north side and flattened, as illustrated in Figure 7-30. In this figure, an open fracture dipping to magnetic south is shown intersecting a drill hole in a three-dimensional drawing on the left. The hypothetical televiewer log on the right shows the fracture as it might appear, as a dark sinusoid, with the low point oriented toward magnetic south. The transducer rotates clockwise, as viewed looking down the well; hence, compass directions are in the order shown at the bottom of the log. Fractures and other openings in the borehole wall or in casing appear as dark areas for several reasons. Increasing well diameter means the acoustic signal must travel farther, and that it will be more attenuated by the fluid in the borehole. In addition, part of the surface of fractures and other openings is not at right angles to the incident acoustic signal, so that it is not reflected back to the transducer.

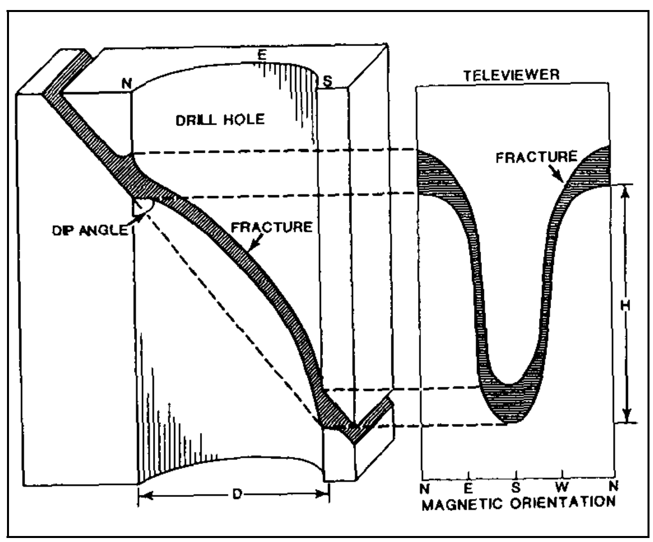


Figure 7-30. Three-dimensional view of a fracture and appearance of the same fracture on an acoustic-televiewer log. D is borehole diameter and h is the length of the fracture intercept in the borehole

(c) Acoustic-caliper log. Modifications to ATV equipment permit recording an acoustic-caliper log, which consists of four high-resolution traces. Use of a lower frequency transducer provides better penetration of casing, and the tool can be used to examine cement in the annular space. Broding (1984) demonstrated the ability of a lower frequency probe to locate voids and channels in cement that were not detected by other logging methods. Acoustic televiewer logs, made in steel casing or in the presence of large concentrations of magnetic minerals, are not oriented, because the magnetometer will not work under these conditions. A switch in the tool can be used for triggering the sweep instead of the magnetometer; as a result, compass orientation of the edge of the log will rotate as the tool is brought up the hole.

(d) Quantitative output. Two quantitative outputs of the acoustic televiewer occur that may require calibration and occasional standardization onsite. The magnetometer needs to be checked with a compass to determine if it triggers on magnetic north within a degree, if possible; this can be accomplished by using a narrow reflective object in a plastic bucket filled with water. The lower set of centralizers usually are removed for this procedure. If an acoustic-caliper log is to be run, hole-diameter response needs to be checked.

(e) Volume of investigation. The concept of volume of investigation does not apply to the televiewer in a strict sense because, with the typical high-frequency transducer, most of the signal is received from the wall of the borehole. Even if the frequency is reduced to half the usual value, rock penetration is small. However, acoustic-televiewer probes have mechanical and electronic limits to the diameter of the well that can be logged. The operating range of borehole diameter for most tools is from 76 to 400 mm (3 to 16 in.).

(f) Interpretation. An acoustic televiewer provides a record of the location, character, and orientation of any features in the casing or borehole wall that alter the reflectivity of the acoustic signal. These include diameter and shape of the drill hole, wall roughness that may be caused by drilling procedures or lithology, differences in rock hardness, and structural features like bedding, fractures, and solution openings. The smallest feature that can be resolved on an ATV log depends on a number of factors; among them are hole diameter and wall roughness. Under the right conditions, features as small as 1 mm, or possibly even smaller, can be identified. Figure 7-31 is a comparison of fractures detected by borehole television, detailed core description, and by the acoustic televiewer at a reactor site in Canada (Davison, Keys, and Paillet 1982). The first two are diagrammatic reconstructions of the fractures, and the ATV log is a copy of the field log. The ATV shows all of the open fractures that are likely to be capable of transmitting water. Borehole television or video missed some of these fractures and some of the fractures shown as dashed on the core log are actually only visible with a hand lens. Paillet (1994) discusses the televiewer and other techniques used to characterize flow in fractured rocks.

(g) Applications. A televiewer log of a fracture-producing zone in a geothermal well at Roosevelt Hot Springs, Utah, is shown in Figure 7-32. Acoustic- and mechanical-caliper logs of this zone are shown in Figure 7-33. These logs were made at temperatures as high as 260˚C (Keys 1979). The fracture-producing interval shown in Figure 7-32 is approximately 1.2 m thick; it apparently is the result of alteration and solution, along a series of subparallel fractures, seen as black sinusoids in the figure. The fracture at the top of the interval appears to be about 150 mm (6 in.) wide, based on the log; it is probably much less. Fractures tend to be broken out during drilling, and the broken edges further increase the apparent thickness on the log by refracting the acoustic signal. This is particularly evident at the top and bottom of the sinusoid on steeply dipping fractures, as illustrated in Figure 7-30. The open fracture in the fracture-producing zone is paralleled by one relatively tight fracture above, and probably six fractures below, which produced a brecciated, and probably altered, permeable zone. The effect of drilling technique and lithology on the interpretation of fracture character from ATV logs is discussed by Paillet, Keys, and Hess (1985). Log quality generally is not as good where the wall of the hole is rough, or where rocks are soft.

(h) Strike and dip. To calculate the strike and dip of fractures or bedding, the following information is needed: the vertical intercept distance on the ATV log H as shown in Figure 7-30; the direction of dip from the ATV log; and, the hole diameter D from a caliper log. The same measuring units must be used for H and D. The angle of dip, in degrees, is equal to the arc tangent of H/D. If the average H for the fractures in Figure 7-30 is 12 in. and the hole diameter is 6 in., the dip would be 63 deg; if the hole diameter is 12 in., the dip would be 45 deg. Direction of dip usually can be measured to the nearest 5 deg, using a 360-deg scale constructed to fit the width of the ATV log. The average direction of dip of the fractures in Figure 7-32 is slightly south of west.

(i) Orientation of stress field. Orientation of the stress field may be determined from an analysis of ATV

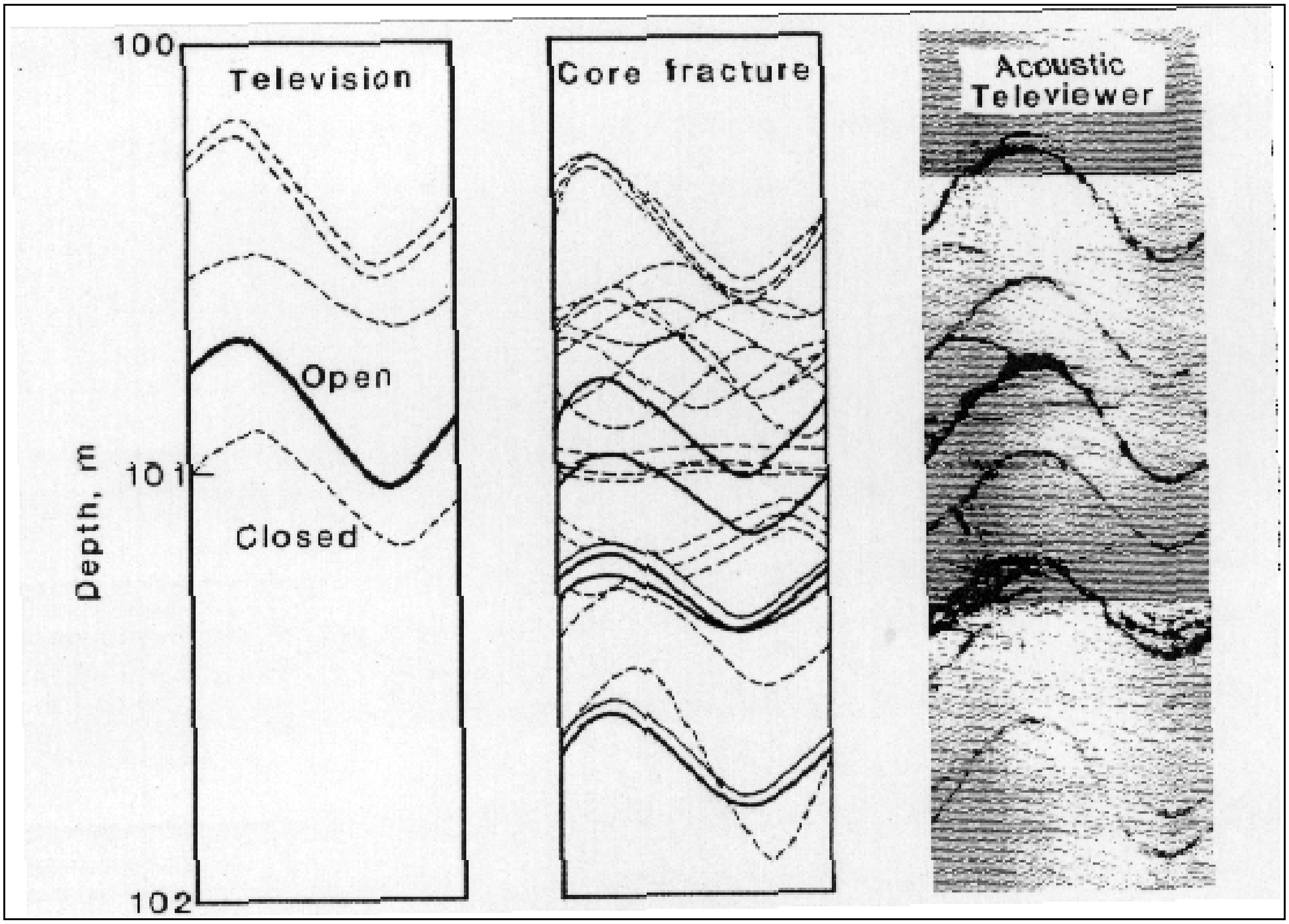


Figure 7-31. Diagram showing comparison of reconstructed fracture data from borehole television, and a detailed core log, with a copy of an acoustic televiewer log

logs made in wells where fractures have been induced hydraulically, either intentionally or accidentally, by drilling (Wolff et al. 1974, Keys et al. 1979). Hydraulic fractures are oriented perpendicular to the direction of least principal stress. Hydraulic fractures accidently induced during drilling may provide permeable pathways for waste migration at environmental sites. Breakouts are increases in borehole diameter oriented at right angles to the maximum, principal, horizontal stress. They are easily recognized on ATV logs and have been discussed in detail by Paillet and Kim (1985). Breakouts appear as two vertical dark bands with irregular margins located approximately 180 deg apart on the log.

(j) Additional applications. The acoustic televiewer can also be used to examine casing for holes and to locate joints in pipe and well screens; borehole television might be better for these purposes if the water is clear and the walls are clean. Above the water level, television needs to be used because the ATV will not operate.

(k) Extraneous effects. Interpretation of televiewer logs is complicated by a number of extraneous effects. Most significant are poor centralization, incorrect gain settings, errors from borehole deviation, and aberrations in the magnetic field. Significant deviation from vertical is common in deep drill holes, which introduces several errors on ATV logs. In addition to the obvious error in the measured vertical depth, corrections must be made to dip and strike calculated from ATV logs in deviated holes. Boreholes are not usually round, and this produces vertical black bands on ATV logs. Poor tool centralization in deviated wells produces similar features on the logs. Choosing the proper gain setting for the tool is a matter of operator experience and is quite important in producing high quality logs.

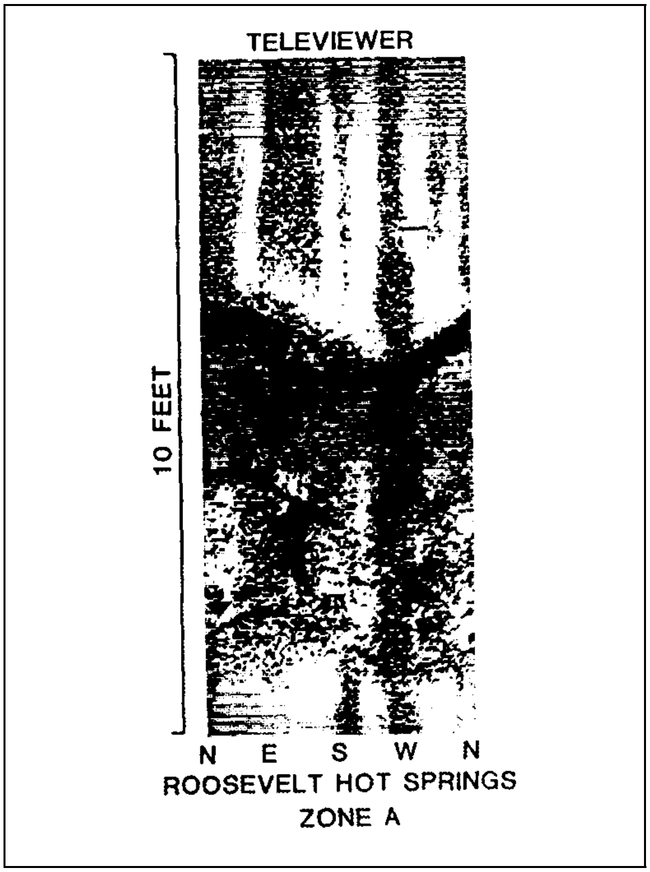


Figure 7-32. Acoustic-televiewer log of fracture-producing zone A in a geothermal well, Roosevelt Hot Springs, Utah

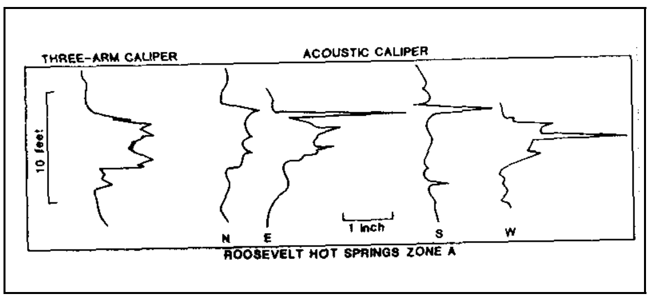


Figure 7-33. Mechanical- and acoustic-caliper logs of fracture-producing zone A in a geothermal well, Roosevelt Hot Springs, Utah

(18) Caliper logging.

(a) Principles. Caliper logs provide a continuous record of borehole diameter and are used widely for groundwater applications. Changes in borehole diameter may be related to both drilling technique and lithology. Caliper logs are essential to guide the interpretation of other logs, because most of them are affected by changes in well diameter. They also are useful in providing information on well construction, lithology, and secondary porosity, such as fractures and solution openings. Many different types of caliper probes are described in detail by Hilchie (1968). The most common type of probe used for logging water wells has three arms approximately the diameter of a pencil, spaced 120 deg apart. Arms of different lengths can be attached to this type of tool to optimize sensitivity over the hole-diameter range expected. Mechanical caliper probes have been used that will measure to a maximum hole diameter of 1 m (42 in.). The typical water-well caliper employs arms that are connected to move a linear potentiometer; so changes in resistance, transmitted to the surface as voltage changes, are proportional to average hole diameter. Single-arm calipers commonly are used to provide a record of hole diameter while running another type of log. The single arm also may be used to decentralize a probe, such as a side-collimated gamma-gamma tool, but logs made with this type of probe are usually not high resolution. High-resolution caliper-logging devices usually employ three or four independent arms, and they are compass oriented in some tools. The difference in resolution between logs made with a four-arm device and the more common types is shown in Figure 7-34. The high-resolution logs on the left were made with four independent arms. The three-arm averaging tool is typical of that used in engineering and environmental applications, and the single arm log on the right was recorded during the running of a compensated gamma-gamma log. The apparent erratic response on the four- arm caliper logs in part of the well is repeatable and is caused by solution openings in the carbonate rock. Digital sample interval should be close spaced, such as 0.03 m (0.1 ft), if high-resolution logs are desired. Acoustic calipers may use the time-of-travel data from an acoustic televiewer to provide compass-oriented, high-resolution traces.

(b) Calibration. Calibration of calipers is carried out most accurately in cylinders of different diameters. Large cylinders occupy a considerable amount of room in a logging truck, so it is common practice to use a metal plate for onsite standardization of three-arm averaging or single-arm probes. The plate is drilled and marked every inch or two and machined to fit over the body of the probe and accept one caliper arm in the holes. Because values obtained with a calibration plate are not as accurate as those obtained with a cylinder, usually log scale is checked using casing of known diameter in the well.

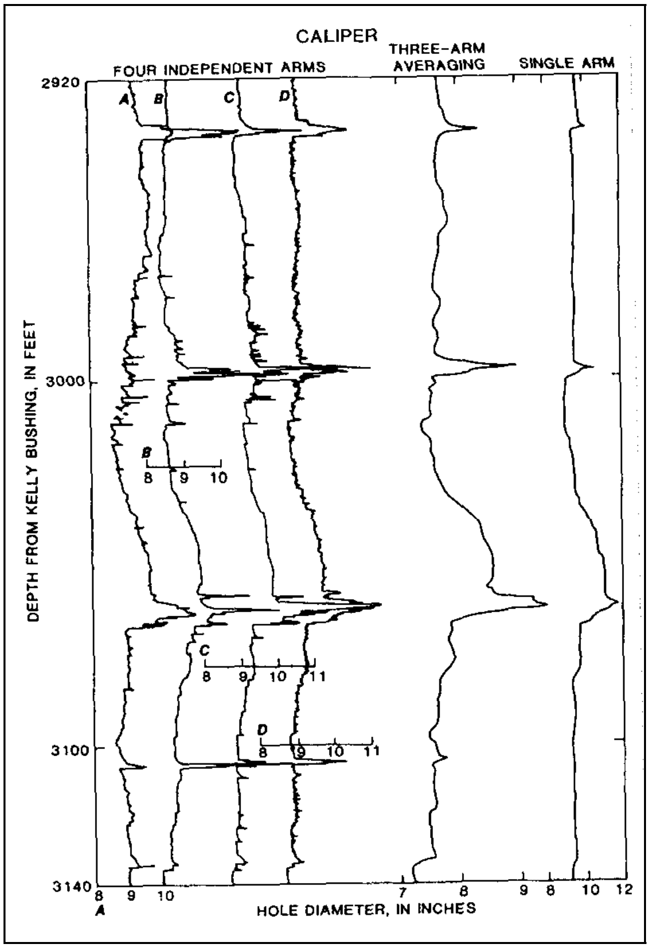


Figure 7-34. Caliper logs from probes having four independent arms, three averaging arms, and a single arm, Madison limestone test well No. 1, Wyoming

(c) Interpretation. A valid caliper log is essential to guide the interpretation of the many different types of logs that are affected by changes in hole diameter, even those that are labeled borehole compensated. Differences in hole diameter are related to drilling technique and lithology and structure of the rocks penetrated. The shallower part of a hole is usually larger diameter than the deeper part, because it has been exposed to more drilling activities. Couplings, welds, and screens may be located on a high-resolution caliper log.

(d) Applications. Caliper logs have been used to correlate major producing aquifers in the Snake River Plain in Idaho (Jones 1961). Vesicular and scoriaceous tops of basalt flows, cinder beds, and caving sediments were identified with three-arm caliper logs. In the Snake River, basalt caliper logs also were used to locate the optimum depth for cementing monitoring wells and to estimate the volume of cement that might be required to achieve fill of the annulus to a preselected depth (Keys 1963). Similarly, a caliper log can be used to calculate the volume of gravel pack needed and to determine the size of casing that can be set to a selected depth. Caliper logs are particularly useful for selecting the depths for inflating packers. Packers can be set only over a narrow specified range of hole diameters and may be damaged if they are set in rough or irregular parts of a well. Packers set under these conditions may explode; if they are set on a fracture, they may implode or be bypassed by flow. Caliper logs are useful for determining what other logs can be run and what range of diameters will be accepted by centralizers or decentralizers. Hole-diameter information is essential for the calculation of volumetric rate from many types of flowmeter logs. Because of the usefulness of a caliper log to the interpretation of other logs, it needs to be run before casing is installed in a hole that is in danger of caving. When hole conditions are questionable, the first log run is usually the single-point resistance log, because it will provide some lithologic information; if it is lost, the tool is relatively inexpensive to replace. If no serious caving problems are detected during the single-point log, a caliper log needs to be run before casing is installed so it can be used to aid the analysis of nuclear logs made through the casing. Very rough intervals of a drill hole, with changes in hole diameter of several inches, cannot be corrected based on caliper logs, and they need to be eliminated from quantitative analysis.

(e) Lithology and secondary porosity. Caliper logs can provide information on lithology and secondary porosity. Hard rocks like limestone will show on the log as a smaller diameter than adjacent shales. Shales may produce an irregular caliper trace, caused by thin bedding. See Figure 7-8 for an example of this response. Secondary porosity, such as fractures and solution openings, may be obvious on a caliper log, although the character will not be uniquely defined as it would be on an acoustic-televiewer log. Four traces from an acoustic-caliper log and a mechanical-caliper log for a fracture-producing zone in a geothermal well at Roosevelt Hot Springs, Utah, are included in Figure 7-33. The oriented traces of the acoustic caliper clearly show the apparent openness of the fractures and the direction of dip of the larger fracture at the top of the zone. These traces also demonstrate that the drill hole is not symmetrical or round, which is a typical condition. Open fractures are detected readily by three-arm averaging calipers but the true character of the fractures may not be correctly interpreted from a caliper log. If an open fracture is dipping at a sufficient angle so that the three arms enter the opening at different depths, the separate anomalies produced will indicate three fractures rather than one.

(19) Fluid logging. Fluid logging includes those techniques that measure characteristics of the fluid column in the well; no direct signal is derived from the surrounding rocks and their contained fluids. The fluid logs that are described here are temperature, electrical conductivity, and flow. Fluid logs are unique in that the recorded characteristics of the fluid column may change rapidly with time and may be altered by the logging process.

(20) Temperature logging.

(a) Principles. Temperature probes used in groundwater and environmental studies employ a glass-bead thermistor, solid-state IC device or platinum sensor mounted in a tube that is open at both ends to protect it from damage and to channel water flow past the sensor. The sensor may be enclosed in a protective cover, but it must be made of materials with a high thermal conductivity and small mass to permit fast response time. Thermistor probes used by the U.S. Geological Survey have an accuracy, repeatability, and sensitivity on the order of 0.02˚C. They also are very stable over long periods of time, but they have the disadvantage of a nonlinear temperature response. For high-temperature logging in geothermal wells, platinum sensors may be used that have an accurate, stable, and linear response. Two general types of temperature logs are in common use: the standard log is a record of temperature versus depth; and the differential-temperature log is a record of the rate of change in temperature versus depth. The differential-temperature log can afford greater sensitivity in locating changes in gradient. The differential-temperature log can be considered to be the first derivative of the temperature; it can be obtained with a probe with two sensors located from 0.3 to 1.0 m apart or by computer calculation from a temperature log. A differential log has no scale and log deflections indicate changes from a reference gradient.

(b) Calibration. Calibration of temperature probes needs to be carried out in a constant temperature bath, using highly accurate mercury thermometers. The bath and probe need to reach equilibrium before a calibration value is established. Onsite standardization cannot be carried out with great accuracy because no portable substitute exists for a constant-temperature bath. The only temperature that can be achieved and maintained for sufficient time to permit a valid calibration is 0˚C, in an ice bath.

(c) Interpretation. Temperature logs can provide very useful information on the movement of water through a well, including the location of depth intervals that produce or accept water; thus, they provide information related to permeability. Temperature logs can be used to trace the movement of injected water or waste and to locate cement behind casing. Although the temperature sensor only responds to water or air in the immediate vicinity, recorded temperatures may indicate the temperatures of adjacent rocks and their contained fluids if no flow exists in the well.

(d) Applications. Temperature logs can aid in the solution of a number of groundwater problems if they are properly run under suitable conditions and if interpretation is not oversimplified. If there is no flow in, or adjacent to, a well, the temperature gradually will increase with depth, as a function of the geothermal gradient. Typical geothermal gradients range between 0.47 and 0.6˚C per 30 m of depth; they are related to the thermal conductivity or resistivity of the rocks adjacent to the borehole and the heat flow from below. The geothermal gradient may be steeper in rocks with low intrinsic permeability than in rocks with high intrinsic permeability.

(e) Thermal gradient. The sensor in a temperature probe only responds to the fluid in its immediate vicinity. Therefore, in a flowing interval, measured temperature may be different from the temperature in adjacent rocks. Under these conditions, a thermal gradient will exist from the well outward. Only in a well where no flow has occurred for sufficient time to permit thermal equilibrium to be established, does a temperature log reflect the geothermal gradient in the rocks. If vertical flow occurs in a well at a high rate, the temperature log through that interval will show little change. Vertical flow, up or down, is very common in wells that are completed through several aquifers or fractures that have different hydraulic head, although the flow rate is seldom high enough to produce an isothermal log. Movement of a logging probe disturbs the thermal profile in the fluid column. Unless rapid flow is occurring, each temperature log will be different. High-logging speed and large-diameter probes will cause the greatest disturbance. The most accurate temperature log is made before any other log, and it is recorded while moving slowly down the hole. Convection is a major problem in the interpretation of temperature logs, particularly in large-diameter wells and in areas of high-thermal gradient. Convective cells in large-diameter wells can cause major temperature anomalies unrelated to groundwater movement (Krige 1939).

(f) Example. Identification of fractures producing groundwater from Triassic sedimentary rocks is illustrated in Figure 7-35. The temperature log on the left shows several changes in gradient that are clearly defined by the computer-derived differential-temperature log. The caliper log suggests that water production may come from fractures; this interpretation is substantiated by the acoustic-televiewer logs, on the right.

(g) Additional applications. Temperature logs can be used to trace the movement of injected water (Keys and Brown 1978). A sampling of several hundred temperature logs run during a 7-day recharge test in the high plains of Texas is shown in Figure 7-36. Water from a playa lake was injected into an irrigation well, and logging was used to determine the movement of the recharge water and the extent of plugging of the Ogallala aquifer. Several monitoring holes were drilled and completed with 2-in. steel pipe, capped on the bottom and filled with water. The logs in Figure 7-36 were of a monitoring hole located 12 m from the injection well. Most of the time, the water in the playa lake was warmer than the groundwater, and the lake temperature fluctuated several degrees each day. The passing of a cold front caused a marked decrease in temperature of the lake water. The first warm water was detected in the monitoring hole less than 4 hr after recharge started. The temperature logs indicated that the interval of highest permeability was located at a depth of approximately 50 m (160 ft). Water did not arrive at a depth of 55 m (180 ft) until the third day. Diurnal temperature fluctuations and buildup of a recharge cone can be observed in Figure 7-36. Data plotted in Figure 7-37 were calculated from temperature logs of the same borehole; however, logs from other holes gave similar results. The solid line in the upper half of Figure 7-37 shows the diurnal-temperature fluctuations of the recharge water obtained from a continuous recorder on the recharge line. The other three lines represent fluctuations at three depths in the monitoring well, as obtained from temperature logs. The points shown by symbols represent the calculated center of the thermal waves. Travel times of the centers of the waves did not decrease during the life of the test, except possibly at the end. Test results show that the aquifer was not plugged by recharging water with a high content of suspended solids and entrained air, and the well yield was greatly increased. Temperature logs can be used to trace the movement of water that has been injected from a tank that has been allowed to heat in the sun. In a similar fashion, temperature logs can be used to locate plumes of wastewater that result from injection in

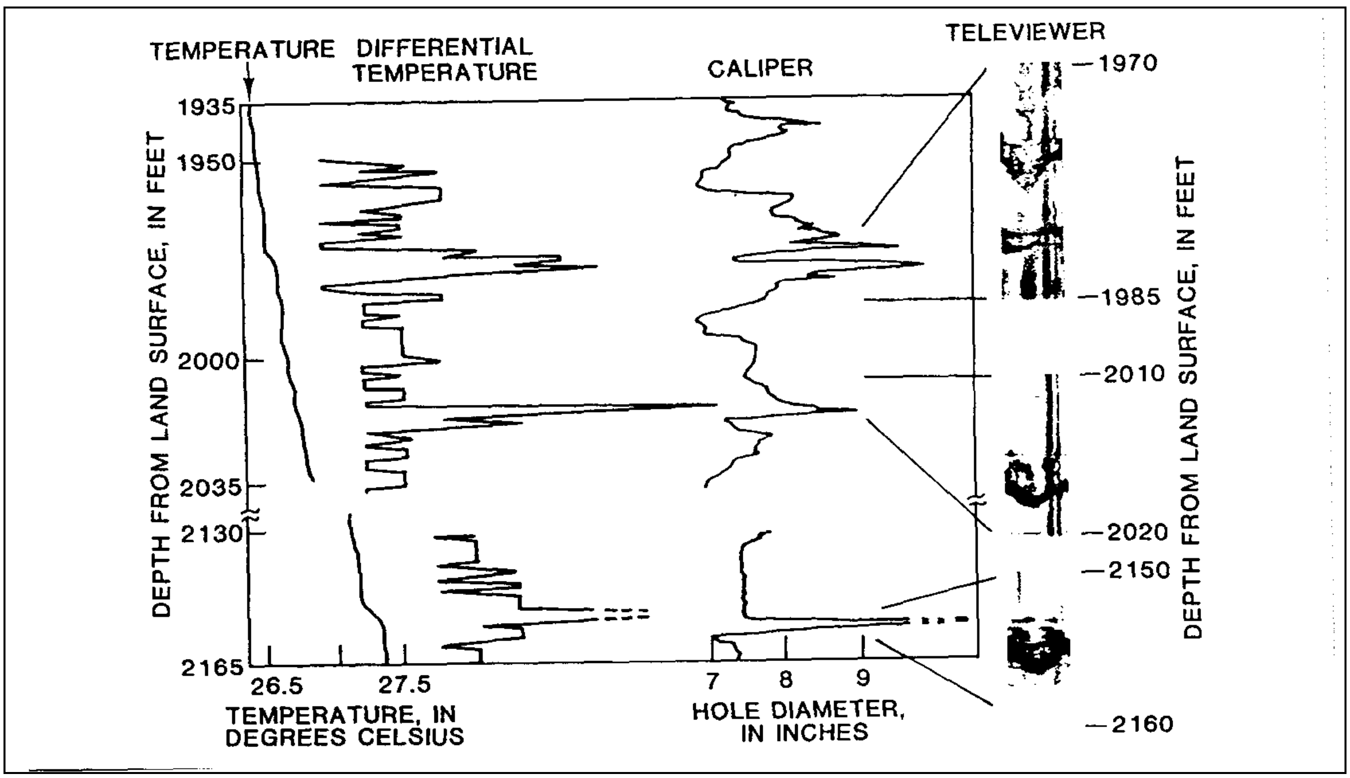


Figure 7-35. Temperature, differential-temperature, caliper, and acoustic-televiewer logs of Sears test well No. 1, near Raleigh, NC

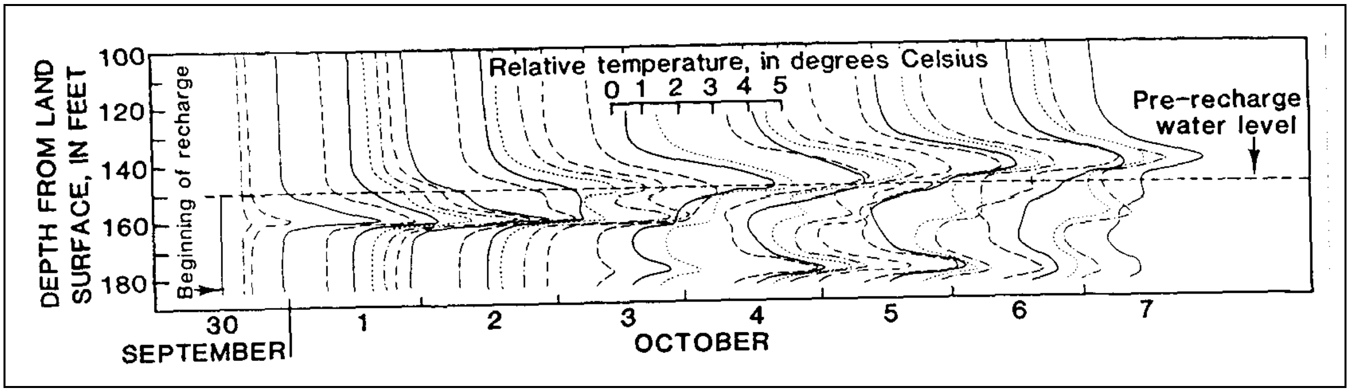


Figure 7-36. Selected temperature logs of a monitoring hole 39 ft from a recharge well, high plains of Texas

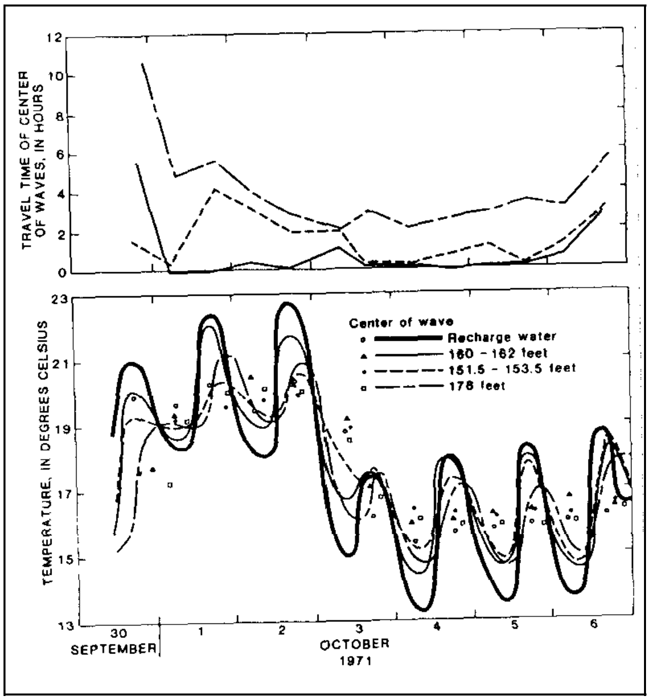


Figure 7-37. Diurnal-temperature cycles and travel times, based on temperature logs of a monitoring hole 39 ft from a recharge well

wells or seepage from ponds, if the wastewater temperature is sufficiently different from the groundwater. Temperature logs also can be used to determine the location of cement grout outside of casing. The casing is filled with water, and the log usually is run within 24 hr of grout injection; however, anomalous temperatures may persist for several days.

(21) Conductivity logging.

(a) Principles. Logs of fluid electrical conductivity, which is the reciprocal of fluid resistivity, provide data related to the concentration of dissolved solids in the fluid column. Although the fluid column may not reflect the quality of adjacent interstitial fluids, the information can be useful when combined with other logs. Fluid-conductivity or resistivity logs are records of the capacity of the borehole fluid that enters the probe to transmit electrical current. The probe should not be affected by changes in the conductivity of adjacent fluids or solid materials because it is constructed with the electrodes inside a housing. Ring electrodes are installed on the inside of a steel tube that is open at both ends, so water will flow through as the probe moves down the well. The electrodes are usually gold or silver to reduce changes in contact resistance caused by chemical reactions, and they are insulated from the steel housing. Conductivity is recorded in µmho/cm or µS/cm, which is equal to 10,000 divided by the resistivity in Ωm. Both units are used for fluid logging, and they can be converted to standard temperature by use of Figure 7-11 or a similar chart. Specific conductance is measured at the standard temperature of 25°C. Calibration usually is done empirically in solutions of known sodium chloride concentration, because most charts are based on this salt, and conversion factors are available to correct for the presence of other ions. The salinity of the calibration solution may be calculated by adding a known amount of salt to distilled water and converting to conductivity, or by measuring with an accurate laboratory conductivity meter. Temperature of the calibration solution is recorded while the measurement is being made, and it needs to be uniform and stable. Onsite standardization may be carried out using several fluids of known concentration in plastic bottles sufficiently large to allow submersion of all electrodes in the probe. A laboratory conductivity cell or a less accurate mud resistivity kit also can be used. Disturbance of the fluid column in the borehole can make fluid-conductivity logs difficult to interpret. Disturbance of an equilibrium-salinity profile can be caused by the movement of logging probes or by convective flow cells. Because of the possibility of disturbance by logging, the most accurate fluid-conductivity log is made on the first trip down the well. This recommendation also pertains to temperature logs, so an ideal probe is capable of making simultaneous fluid-conductivity and temperature logs.

(b) Interpretation. The interpretation of fluid-conductivity logs is complicated by the flow regime in a well. Unless the flow system is understood, analysis of the conductivity profile is subject to considerable error. Information on the construction of the well, flowmeter logs, and temperature logs are useful in the interpretation of conductivity logs. When both fluid conductivity and temperature are known, the sodium chloride concentration can be determined from Figure 7-11. Water samples must be analyzed to determine the concentrations of the various ions so corrections can be made.

(c) Applications. Regional patterns of groundwater flow and recharge areas may be recognized from fluid-conductivity logs of the wells in an area. Fluid-conductivity data can be used to map and monitor areas of saltwater encroachment. Similarly, the logs can be used to monitor plumes of contaminated groundwater from waste-disposal operations. Commonly, chemical waste or leachate from solid-waste-disposal operations produces groundwater with a higher than normal conductivity. Conductivity logs provide the basis for selecting depths from which to collect water samples for chemical analyses. Fluid-conductivity logging equipment can be used to trace the movement of groundwater by injecting saline water or deionized water as a tracer. Small amounts of saline water may be injected at selected depths, and conductivity logs may be used to measure vertical flow in a single well, or larger amounts may be detected in nearby wells. Another important use for fluid-conductivity logs is to aid in the interpretation of electric logs. Spontaneous potential, single-point resistance, and many types of multi-electrode-resistivity logs are affected by the salinity of the fluid in the well.

(22) Flow logging.

(a) Principles. The measurement of flow within and between wells is one of the most useful well-logging methods available to interpret the movement of groundwater and contaminants. Flow measurement with logging probes includes mechanical methods, such as impellers, chemical and radioactive tracer methods, and thermal methods (Crowder, Paillet, and Hess 1994). Their primary application is to measure vertical flow within a single well, but lateral flow through a single well or flow between wells also may be recorded by borehole-geophysical methods.

(b) Impeller flowmeter. The most common logging probe used at the present time for measuring vertical fluid movement in water wells is the impeller flowmeter, which is a relatively inexpensive and reliable instrument. Most impeller flowmeters incorporate a lightweight three- or four-bladed impeller that rotates a magnet mounted on the same shaft. The magnet actuates a sealed microswitch, so that one or more pulses are impressed on low-voltage direct current that is connected across the switch. The impeller is protected from damage by a basket or housing, and the probe is centralized with bow springs, or similar devices, for best results. Baskets and impellers of different diameters are available and are easily changed, so the maximum size for a well can be used to increase sensitivity. Continuous logs of flow rate may be made at a constant logging speed and supplemented by more accurate stationary measurements at selected depths. The main shortcoming of impeller-type flowmeters is the lack of sensitivity to low-velocity flow. The most commonly used impeller flowmeters usually stall at vertical velocities of 1.2 to 1.5 m/min (4 to 5 ft/min), although it is possible to measure velocities as low as one half those velocities under some conditions. The addition of a packer or other flange-like device to divert most of the flow through the basket will improve sensitivity to low velocity, particularly in large-diameter wells.

(c) Tracer techniques. Tracer methods have been used in groundwater for many years, but only those that employ logging equipment are described here. Tracer techniques are useful at much lower velocities than impeller flowmeters; rates of about 1 m/day may be detected. The most commonly employed methods use a probe to follow the vertical movement of a chemical or radioactive tracer injected at selected depths in a well. An extension of this method may permit the detection of arrival of the tracer by logging adjacent wells. Radioactive tracers can be detected at lower concentrations than chemical tracers; most of them can be detected through casing. The difficulties in obtaining the permits necessary for using radioactive tracers has restricted their application. Temperature and fluid conductivity logs can also be used to measure flow rates between wells.

(d) Heat-pulse flowmeters. A heat-pulse flowmeter originally was developed in England (Dudgeon, Green, and Smedmor 1975). Its design was modified extensively, and a new probe was built by A. E. Hess of the U.S. Geological Survey (Hess 1982). The modified version works reliably and has been used in wells to measure very low velocities, as described in paragraph 7-1*j*(22)(g) "Interpretation and Applications." The logging system is shown schematically in Figure 7-38, modified from Hess (1982). The wire heat grid, located between two thermistors, is heated by a 1-ms pulse of electric current which is triggered from the surface. The heated sheet of water moves toward one of the thermistors under the influence of the vertical component of flow in the well. The arrival of the heat pulse is plotted on a chart recorder running on time drive, as illustrated in Figure 7-39. A deflection of the recorder trace to the right indicates upward flow, and to the left, downward flow. The system is calibrated in flow columns of various sizes for flow in each direction, because the tendency for heated water to rise and the asymmetry of the probe produce slightly different calibration curves in the two directions. The USGS heat-pulse flowmeter can be used to measure vertical-water velocities from 30 mm/min or less to 12 m/min or greater (0.1 to 40 ft/min), and it has advantages over both impeller flowmeters and tracer logging. An inflatable packer or flexible diverter can be attached to a flowmeter to force all flow through the probe and, thus, improve the performance of the heat-pulse flowmeter. A similar heat pulse flowmeter is now available commercially. A number of techniques have been tried for measuring horizontal flow in wells without much success or wide use. The technique may not provide an accurate estimate of average direction and velocity of flow in the aquifer, because of the perturbations in the flow system caused by the well. A heat-pulse logging system has been developed for measuring horizontal flow (Kerfoot 1982); it employs a series of paired thermistors located circumferentially around a heat emitter, and it is based on thermal transmission through an enclosing porous matrix of glass beads.

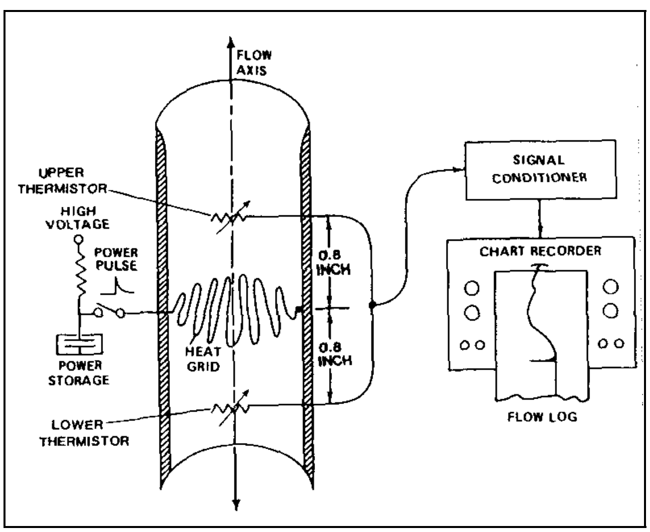


Figure 7-38. Equipment for making heat-pulse flowmeter logs (Hess 1982)

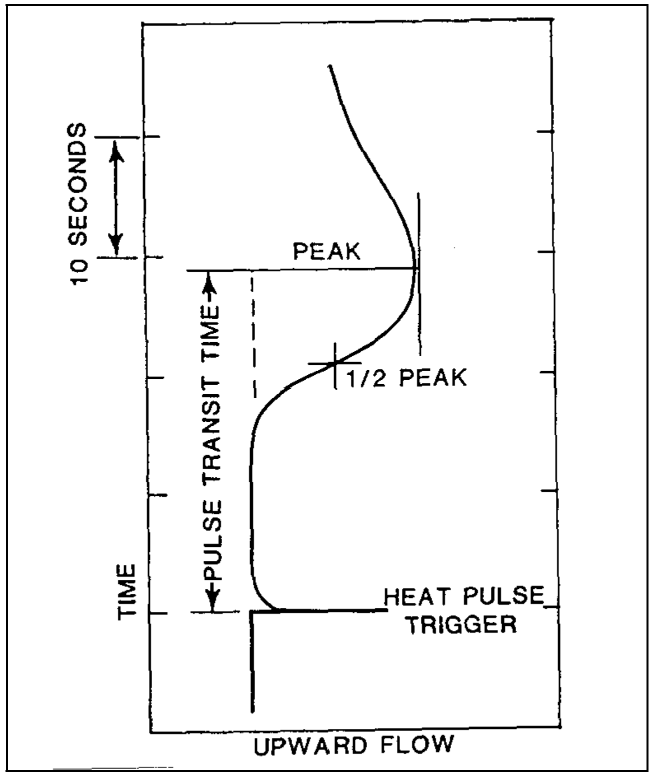


Figure 7-39. Analog record of a heat pulse from a thermal flowmeter (Hess 1982)

(e) Calibration. Calibration of flow-measuring probes is done best in laboratory facilities designed for this purpose. Subsequent calibration checks and standardization may be carried out in a well under the proper conditions. The U.S. Geological Survey has designed and built a facility that is used for calibrating their flow-measuring probes (Hess 1982). The test facility consists of clear plastic columns with inside diameters of 2, 4, and 6 in. connected to a pump that can circulate water in either direction, at velocities from 21 mm to 15 m/min (0.07 to 50 ft/min), depending on column size. Onsite standardization or calibration can be performed by moving the flowmeter up or down a cased portion of a well at carefully controlled logging speeds. Calibration by this method is only valid at the casing diameter logged. An example of this type of calibration is shown in Figure 7-40, where the pulses per unit time are plotted against the logging speed. The two lines with different slopes represent opposite directions of impeller rotation. The range of tool speeds near this intersection represents the stall zone where the velocity is too low to turn the

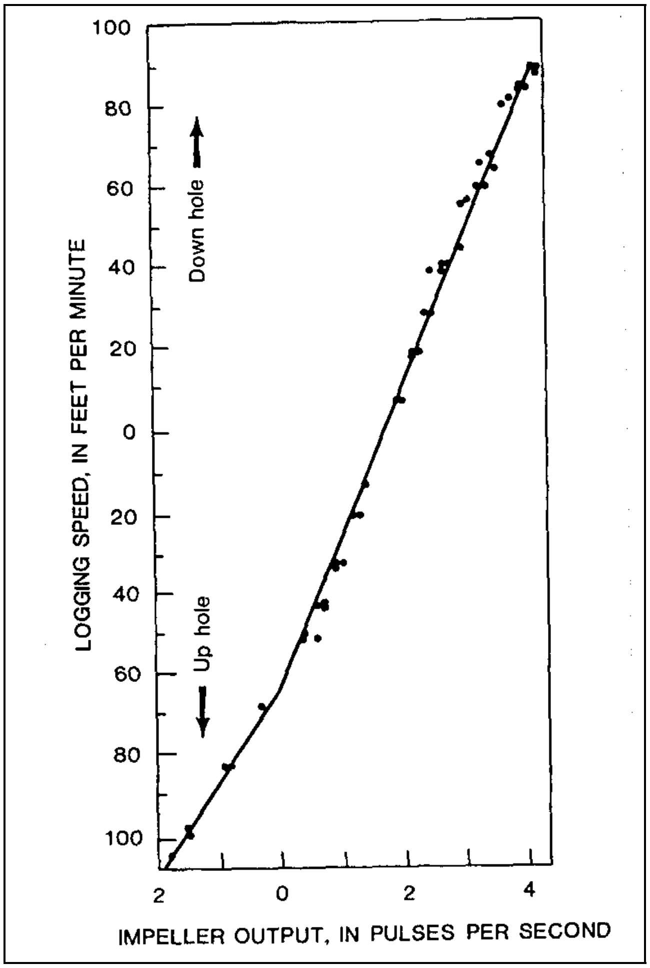


Figure 7-40. Calibration data for an impeller flowmeter, developed by moving the probe in a well

impeller. Theoretically, this intersection represents the velocity at which water was flowing up the well.

(f) Hydrophysical logging. Fluid replacement and fluid-column conductivity logging, known by the trade name "Hydrophysical" logging (Pedler et al. 1990; Pedler, Head, and Williams 1992; Tsang, Hufschmied, and Hale 1990) involves fluid column conductivity logging over time after the fluid column has been diluted or replaced with environmentally safe deionized water. Hydrophysical logging results are independent of borehole diameter and the method does not require a flow concentrating diverter or packer. The logging probe involves relatively simple and readily available technology and has a small diameter allowing it to be run through an access pipe below a pump. Hydrophysical logging is used to determine flow magnitude and direction during pumping and under ambient conditions, and to identify hydraulically conductive intervals to within one wellbore diameter. Figure 7-41 is a schematic drawing of the equipment used to replace the borehole fluid with deionized water and to subsequently run a series of fluid conductivity logs to record the inflow of formation fluids.

(g) Interpretation and applications. Interpretation of flowmeter logs is simple if the probe has been properly calibrated and if all the essential information on hole diameter and construction is available. Vertical flow is common in most wells that are open to more than one aquifer and flow can be induced by pumping or injecting water. The heat-pulse flowmeter developed by Hess (1982) was used first in the field to identify fractures producing and accepting water in granitic rocks (Keys 1984). A caliper log and data from the heat-pulse flowmeter are shown in Figure 7-42. Data from the heat-pulse

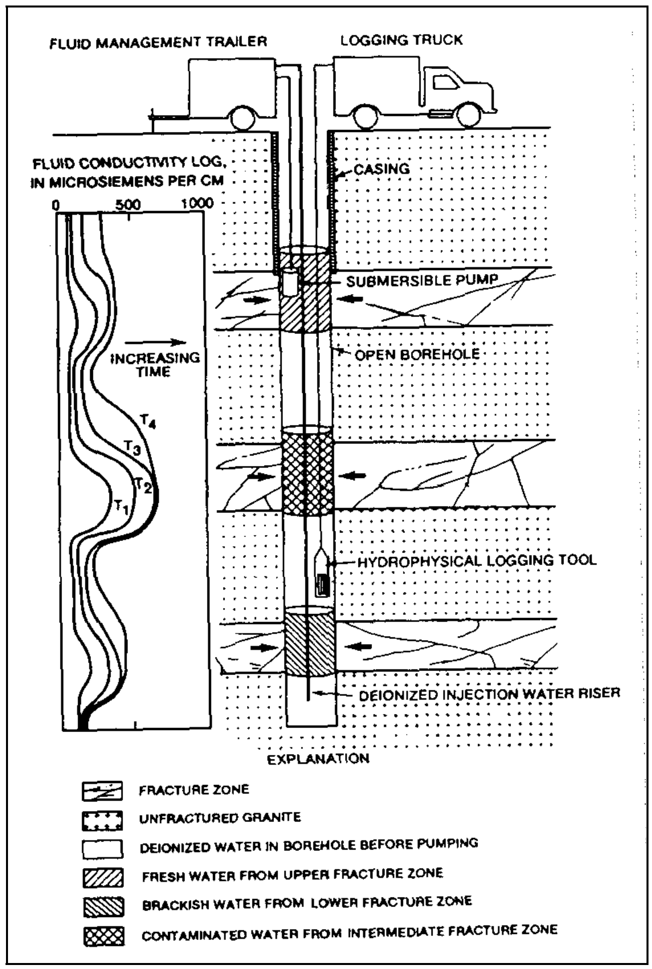


Figure 7-41. Schematic drawing of equipment used for hydrophysical logging after injection of deionized water; and time series of fluid conductivity logs (Vernon et al. 1993; copyright permission granted by Colog, Inc.)

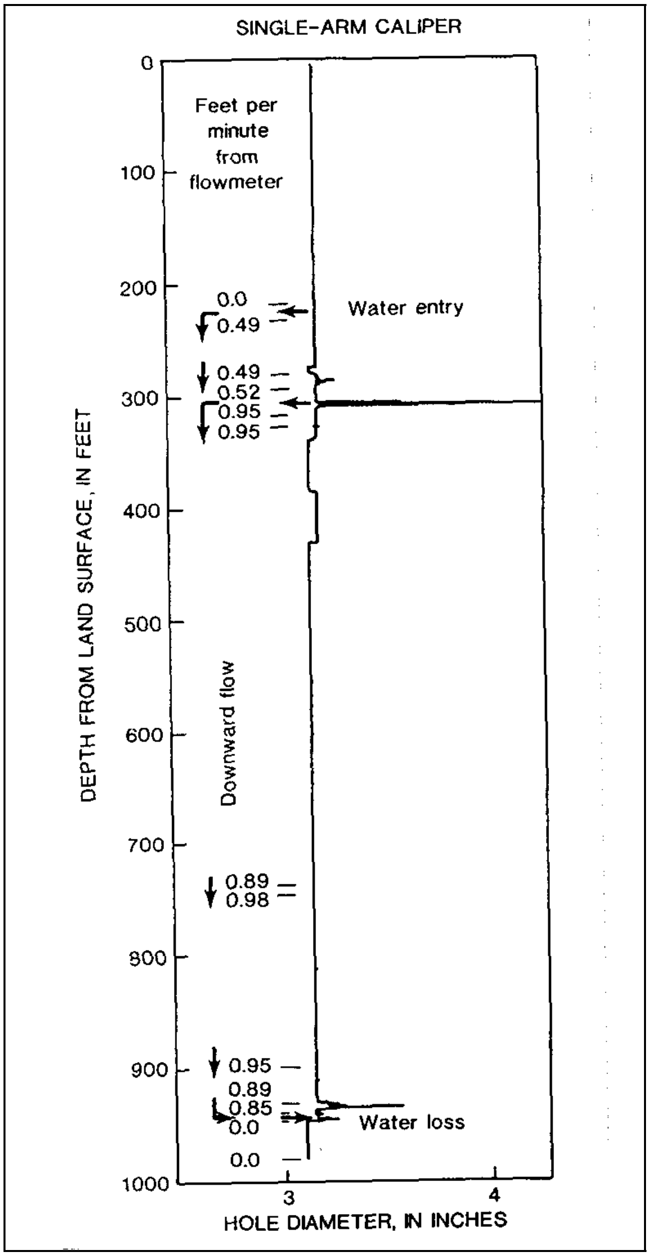


Figure 7-42. Single-arm caliper log on the right and data from heat pulse flowmeter showing zones of water entry and exit

flowmeter were quite reproducible over a period of 2 weeks, even though pumping and injection tests being conducted in a well approximately 300 m from the logged well caused short-term changes. The flowmeter logs and acoustic-televiewer logs at this site enabled the characterization of permeable fractures. In Figure 7-42, the upper fracture zone, at a depth of approximately 300 ft (90 m), and the lower zone, at a depth of approximately 940 ft (290 m), both contain thin, discrete fractures that are transmitting much of the water, rather than thicker, complex fractures within each zone. Note that slightly less than half of the flow from the upper zone originates in the fracture at a depth of 308 ft (94 m), although that fracture appears to be the widest on the caliper log. Similarly, the fracture that appears to be the largest in the lower zone is accepting only a small percentage of the flow. Acoustic televiewer logs indicated that the same two fracture zones were intersected in other wells in the area and appear to constitute major aquifers. Paillet, Crowder, and Hess (1994) present a detailed description of how the heat pulse flowmeter, in combination with acoustic televiewer logs, can be used to characterize the hydraulic properties of fracture systems that intersect multiple drill holes.

(h) Finite difference modeling software. A critical element in the application of hydrophysical logging compared to established conductive tracer technology is the development of finite difference modeling software routines to simulate the data obtained in the field. This software also permits the calculation of permeability. The method can also be expanded to measure other properties such as water temperature and pH, in order to determine the properties of the formation water entering the borehole. Therefore, fluid replacement logging can indicate the quality and physical properties of water entering the borehole along with the magnitude and direction of flow. In theory, there are no upper or lower limits to the magnitude of flow that can be detected. Published field studies demonstrate that the technique has achieved better low-flow resolution than that reported with other flow measurement techniques (Vernon et al. 1993).

(23) Well-completion logging. Logging to determine the construction of a well is useful for the planning of cementing operations, installation of casing and screens, hydraulic testing, and guiding the interpretation of other logs. Most of the logs described in other sections of this manual can provide information on well construction under some conditions. They will be listed briefly here so the reader can refer to the detailed descriptions of these logs in the appropriate sections of this manual.

(24) Casing logging.

(a) A number of different types of logs can be used to locate cased intervals in wells. Most electric logs will show a sharp deflection at the bottom of a string of steel casing. Resistivity-logging systems that are operating properly will record zero resistivity when all the electrodes are in the casing. Gamma-gamma logs commonly demonstrate a sharp deflection at the bottom of the casing and may shift at depths where a second string of casing is located outside the first; however, such shifts may be difficult to distinguish from changes in hole diameter. High-resolution caliper logs are excellent for locating the bottom of the inside string of casing and for locating threaded couplings. If small arms are used, they also may provide data on casing corrosion and the location of screens and perforations. Care must be taken to assure that the arms do not get caught in screens or perforations.

(b) The acoustic televiewer is one of the highest resolution devices for obtaining information on casing and screens, but it may be too expensive for some operations. The televiewer must be operated on the mark switch in steel casing, rather than magnetometer, to avoid distortion of the log caused by random triggering. Televiewer logs can provide clear images and accurate locations of screens, perforations, couplings, and damaged casing. Features as small as 1 mm can be resolved under the right conditions. Borehole television can provide some of the same data, but a hard copy of the log is not available for examination at any time. The water in the well also must be clear to allow light transmission.

(c) The casing-collar locator (CCL) is a useful and relatively inexpensive device that can be operated on any logging equipment. The simplest CCL probe contains a permanent magnet wrapped with a coil of wire. Changes in the magnetic properties of material cutting the magnetic lines of flux cause a small DC current to flow, which can be used to drive a recorder channel. The standard mode of operation is to record event marks along the margin of other logs to represent the location of collars in the casing. The event marker is adjusted so that it is triggered when the DC voltage exceeds a certain level. A continuous-collar log can be interpreted in terms of the location of perforations and screens. Corroded casing sometimes can be located by a high-resolution caliper log; spontaneous-potential logs have been used to locate depth intervals where active corrosion is taking place (Kendall 1965). Commercial-logging services are available for detecting corroded casing. An electromagnetic casing-inspection log measures changes in the mass of metal between two coils; loss of mass may be due to corrosion (Edwards and Stroud 1964). A pipe-analysis survey is run with a centralized probe that employs several coils (Bradshaw 1976). This survey is reported to provide information on the thickness of casing penetrated by corrosion, whether the damage is internal or external, and isolated or circumferential. The electromagnetic-thickness survey measures the average casing thickness over an interval of about 0.6 m and can be used to monitor changes in thickness with time. Casing-inspection logging methods are summarized by Nielsen and Aller (1984).

(25) Logging annular materials.

(a) The location of cement, bentonite, and gravel pack in the annular space outside of casing can be accomplished with several logs, but the interpretation may be ambiguous. A caliper log made before the casing is installed is important to planning cementing or installation of gravel pack. Caliper logs also are useful in interpreting logs run for the purpose of locating annular material, because they indicate the thickness that would be present.

(b) Temperature logs can be used to locate cement grout while it is still warm from setup reactions. Cement-bond logs can be used to locate cement after it has cured, and they may provide information on the quality of the bond between casing and cement and between cement and rock. Uncompensated, short-spaced gamma-gamma logs can indicate the location of cured cement or gravel pack, if a gamma-gamma log was run after installing the casing and prior to filling the annular space; the difference between the two logs may show the filled interval clearly. The pre-cementing gamma-gamma log may resemble the reversed caliper log made prior to installation of the casing. The location of bentonite often is indicated by an increase in radioactivity on gamma logs; however, all bentonite is not more radioactive than the various background materials that might be present.

(c) Acoustic cement bond logging was developed for annular cement evaluation in oil and gas production wells (Bateman 1985). The interpretation of cement bond logs involves the analysis of the amplitude of the compression wave arrival, and the full wave form display. Where pipe, cement, and formation are well bonded, the full wave form display indicates that the acoustic energy from the logging probe is being transmitted to the formation (a formation response is evident). Furthermore, for the case of continuous cement in the annular space with no voids or channels, the compression wave amplitude is a minimum, increasing where the cement is discontinuous.

(d) A quantitative method employing gamma-gamma density logs calibrated for backfill materials is shown in Figure 7-43 (Yearsley, Crowder, and Irons 1991). Below the water surface the saturated sand pack is indicated by a far detector measurement of 1.9 g/cc, and a near detector measurement of 1.7 g/cc, values that were confirmed by physical modeling. The difference in densities between the near and far detectors is due to the greater effect of

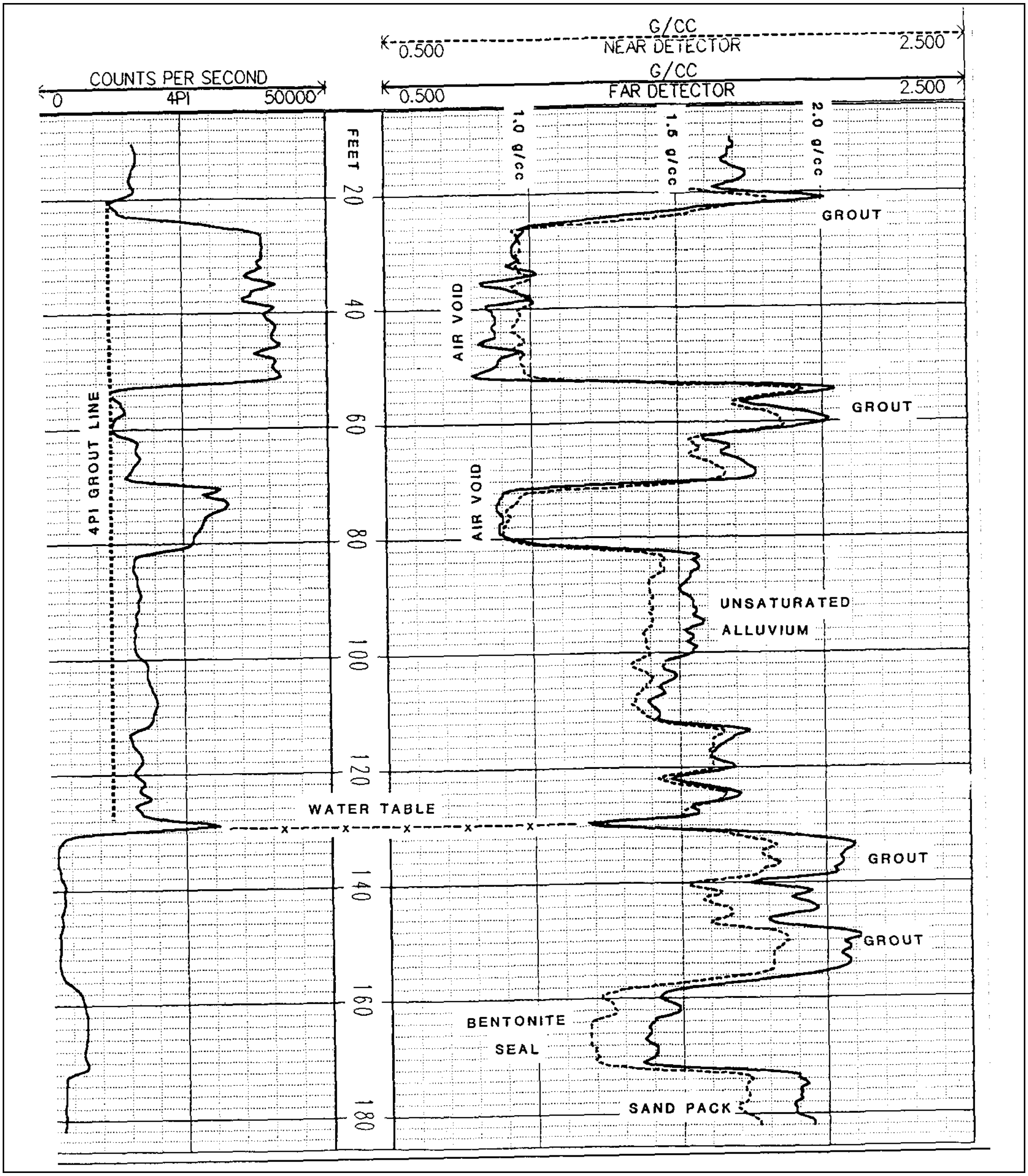


Figure 7-43. Dual-spaced and "4π" density logs in a cased monitoring well showing completion as interpreted from the logs (Yearsley, Crowder, and Irons 1991; copyright permission granted by Colog, Inc.)

the low-density PVC on the near detector. The bentonite slurry seal is less dense than the sand pack, and is readily recognized on the geophysical log, but appears to be 12 ft (3-2/3 m) thick rather than the 5 ft (1-1/2 m) specified on the completion schedule. The water surface is identified by an increase in the 4π count rate above a depth of 130 ft (40 m). Also note at the water surface the low densities registered by the near and far detectors and high count rate anomaly on the 4π log, which indicate a wash-out at that depth. The cement/bentonite grout below the water surface may be indicated by far detector densities greater than 2.0 g/cc, and near detector densities of approximately 1.8 g/cc. The distinct density contrasts above the water surface in Figure 7-43 result from the density differences among grout, unsaturated alluvium, and air voids. Air voids behind pipe on this log are identified by densities of approximately 1.0 g/cc for both the near and far detectors. Grout above the groundwater surface is interpreted for far detector densities ranging between 1.6 and 2.0 g/cc. The range in density is due primarily to variations in grout thickness. Unsaturated alluvium is indicated by far detector densities between 1.4 and 1.6 g/cc. On the left of Figure 7-43 is a "4π grout line," which indicates the expected 4π count rate in a 4-in. PVC air-filled pipe with 6:2 cement:bentonite grout behind the pipe.

(26) Borehole-deviation logging.

(a) Deviation of drill holes and wells from the vertical is common; it affects proper completion of the well for its intended use, and it may prevent testing and logging. Casing and pumps may be impossible to install in a well that is highly deviated, and centralized logging probes may not function properly in such a well. The deviation seldom is consistent, so that both the angle from the vertical and direction may change rapidly along the borehole. Even auger holes less than 30 m deep have deviated enough that transmittance logs between the holes are adversely affected. Information on borehole deviation is needed to calculate the true vertical depth to features of interest and to correct the strike and dip of fractures or bedding obtained from such logs as the acoustic televiewer.

(b) Continuous logs of hole deviation usually are run by companies that specialize in this technique. Hole-deviation data usually are not recorded by standard logging equipment, except modern dipmeters, which rarely are included on small loggers. A dipmeter log usually includes a continuous record in the left track of the azimuth (magnetic north) and the amount of deviation. Some hole-deviation services provide a printout of azimuth and deviation at predetermined depth intervals, and there are several methods to mathematically describe the path of the deviated hole from these measurements (Craig and Randall 1976).

7-2. General Crosshole Procedures

a. Introduction. The primary purpose of obtaining crosshole data is to obtain the most detailed in situ seismic-wave velocity profile for site-specific investigations and material characterization. Crosshole velocity data are valuable for assessing man-made materials, soil deposits, or rock formations.

(1) The seismic technique determines the compressional (P-) and/or shear (S-) wave velocity of materials at depths of engineering and environmental concern where the data can be used in problems related to soil mechanics, rock mechanics, foundation studies, and earthquake engineering. Crosshole geophysical testing is generally conducted in the near surface (upper hundred meters) for site-specific engineering applications (Sirles and Viksne 1990). All of a material's dynamic elastic moduli can be determined from knowledge of the in situ density, P-, and S-wave velocity. Therefore, since procedures to determine material densities are standardized, acquiring detailed seismic data yields the required information to analytically assess a site. Low-strain material damping and inelastic attenuation values can also be obtained from crosshole surveys. However, the most robust application of crosshole testing is the ability to define in situ shear-wave velocity profiles for engineering investigations associated with earthquake engineering (Mooney 1984).

(2) The objective of acquiring crosshole data can be multipurpose; that is, the seismic velocity results obtained may be used for evaluation of lateral and vertical material continuity, liquefaction analyses, deformation studies, or investigations concerning amplification or attenuation of strong ground motion. Typically, crosshole surveys are a geophysical tool for performing explorations during what are considered phase two field investigations (where phase one field investigations include surface geophysical surveys, follow-up drilling, trenching, and sampling of the in situ materials). During phase two field exploration, the information gathered is more critical to the analytical site-specific characterization. Although both phase one and phase two results are important, the two independent sets of data must be integrated into the final analysis.

(3) Crosshole techniques are most useful when phase one site explorations indicate horizontal and particularly vertical variability of material properties. When layers of

alternating density or stiffness are either known to exist or are encountered during phase one field investigations, then crosshole seismic tests are recommended to define the in situ velocities within each layer. Acquiring crosshole seismic data resolves hidden layer velocity anomalies which cannot be detected with conventional surface methods, allows both final interpretation of other surface geophysical data (seismic or electrical), and permits both empirical and theoretical correlation with other geotechnical material parameters.

(4) In order to have quantitative and quality assured results, crosshole tests performed for either engineering or environmental problems should be conducted in accordance with procedures established by the American Society for Testing and Materials (ASTM). Crosshole seismic test procedures are outlined in ASTM test designation D4428 M-84 (1984). The ASTM procedures provide specific guidelines for borehole preparation, data acquisition, and data reduction/interpretation. Based on ten years of experience, since the inception of the ASTM standard in 1984, crosshole geophysical surveys have become more widely used and accepted for engineering as well as environmental applications. Coupling detailed site information obtained from the crosshole tests with the overall acceptance of the validity of the velocity data, these standards use both empirical correlations for liquefaction and specific input parameters for deformation or ground motion analyses (U.S. Bureau of Reclamation 1989).

b. Theory and equipment.

(1) Crosshole testing takes advantage of generating and recording (seismic) body waves, both the P- and S-waves, at selected depth intervals where the source and receiver(s) are maintained at equal elevations for each measurement. Figure 7-44 illustrates a general field setup for the crosshole seismic test method. Using source-receiver systems with preferential orientations in tandem (i.e., axial orientations, which compliment the generated and received wave type/signal) allows maximum efficiency for measurement of in situ P- or S-wave velocity depending on the axial orientation. Due to the different particle motions along the seismic raypath it is crucial to use optimal source-receiver systems in order to best record crosshole P- or S-waves (Hoar 1982). Because only body waves are generated in the source borehole during crosshole tests, surface waves (ground roll) are not generated and do not interfere with the recorded body-wave seismic signals.

(2) Stokoe (1980) demonstrated that particle motions generated with different seismic source types used during crosshole testing are three-directional. Therefore, three-component geophones with orthogonal orientations yield optimal results when acquiring crosshole P- and/or S-wave seismic signals. With three-component geophones there is one vertically oriented geophone and there are two horizontal geophones. For crosshole tests one horizontal geophone remains oriented parallel to the axis between the boreholes (radial orientation) and the other one remains oriented perpendicular to the borehole axis (transverse orientation). In this case, the two horizontal axis geophones must remain oriented, radially and transversely, throughout the survey. This is accomplished with loading poles or with geophones that can be electronically oriented.

(3) P-waves are generated with a sparker or small explosive device (one that will not damage the PVC casing) such that along the assumed straight-ray propagation path the seismic impulse compresses and rarefies the materials radially toward the receiver borehole(s). Experience has proven that for optimal measurement of the P-wave signal, a hydrophone has the greatest pressure-pulse sensitivity for compressional-wave energy. Also, hydrophones do not need to be clamped against the borehole wall; however, water must be present in the receiver borehole in order to couple the hydrophone to the casing/formation.

(4) For either surface or crosshole seismic testing in unconsolidated materials, P-wave velocity measurements are greatly affected by the moisture content or percent saturation (Allen, Richart, and Woods 1980). In crosshole testing the seismic measurements encroach closer to the water surface with each successive depth interval. As the vadose zone and water surface are encountered, P-wave velocities become dependent upon the percent saturation and the Poisson's ratio is no longer a valid representation of the formation characteristics (e.g., Poisson's ratio increases to 0.48-0.49 in 100 percent saturated soils). Hence, below the water surface the P-wave is commonly termed the fluid wave, because its propagation velocity is governed by the pore fluid(s); not the formation density. Fluid-wave velocities in fresh water range from 1,400 to 1,700 m/s, depending upon water temperature and salt content.

(5) S-waves generated in crosshole testing may be split into two wave types, each with different particle motions; SV- and SH-waves, vertical or horizontal

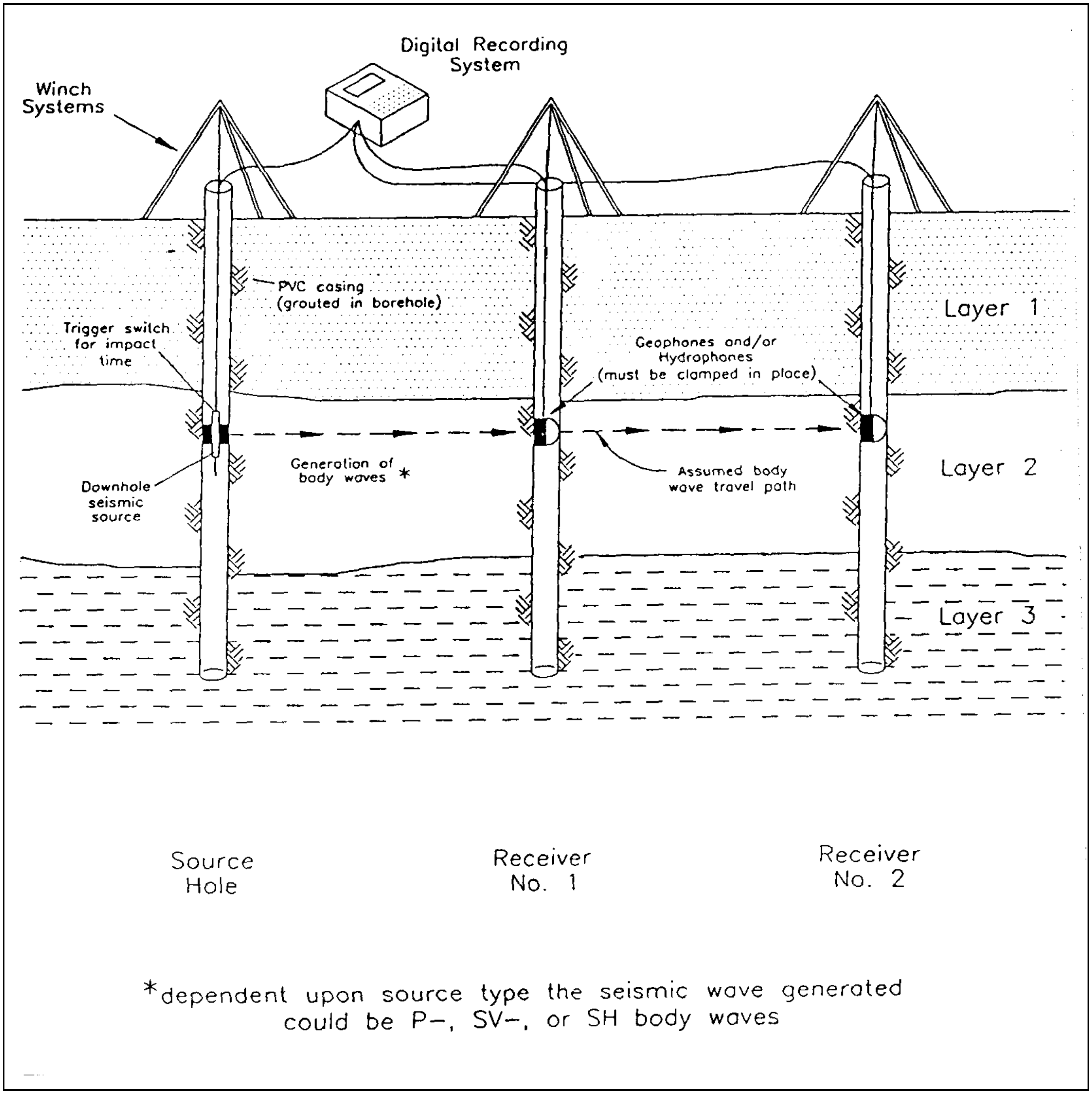


Figure 7-44. Schematic of crosshole seismic method

particle motions, respectively. Shear waves have the unique capability of polarization, which means that impacting the material to be tested in two directions (up or down, left or right) yields S-wave signals which are 180 deg out of phase. A seismic source with reversible impact directions is the key factor for quality crosshole S-wave data acquisition and interpretation. Figure 7-45 shows a series of crosshole SV-waves with reversed polarity (note the low amplitude of the P-wave energy compared to the S-wave energy) received at both receiver boreholes.

(6) Typically, the S-wave generated in most cross-hole testing is the SV-wave, which is a vertically polarized horizontally propagating shear wave. That is, the

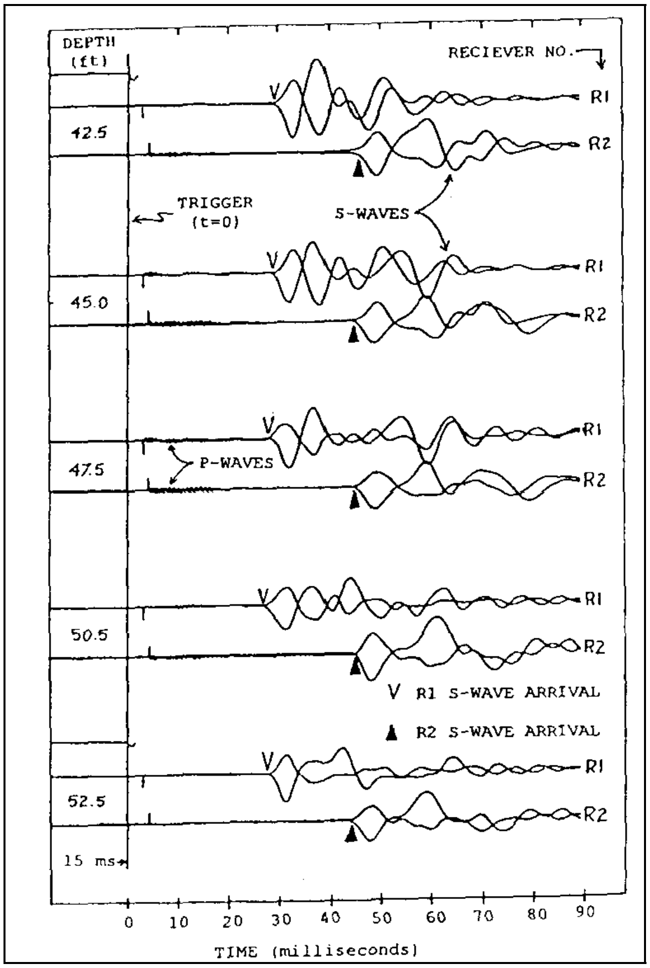


Figure 7-45. Crosshole SV-wave paired-borehole records at five depths

raypath is horizontal but the (shear) particle motion along the raypath is in the vertical plane. These SV-waves are easiest to generate because of commercially available borehole impact hammers which have reversible impact directions (up or down) and they are also the easiest to record because only one vertically oriented geophone is required in each receiver borehole. Alternatively, SH-waves can be generated and recorded in crosshole testing. SH-waves also propagate horizontally, but their (shear) particle motion is in the horizontal plane (i.e., horizontally polarized horizontally propagating S-waves). Therefore, in order to generate and record SH-wave signals horizontal impacts and geophones are required; also, the orientation of the source and receiver must be parallel while their respective orientation remains perpendicular to the axis of the boreholes (transverse orientation).

(7) Theoretically, there is no difference in the body wave velocity for SV- and SH-waves, which justifies use of the uncomplicated vertical source for generation of SV-waves, and vertically oriented geophones for signal detection. There are studies, however, which indicate significant velocity dependence of the SV- and SH-waves due to anisotropic states of stress in either the horizontal or vertical stress field (particularly in soil deposits; Redpath et al. (1982)) or fractured rock formations (White 1983).

(8) The requirement for multiple drill holes in crosshole testing means that care must be taken when completing each borehole with casing and grout. ASTM procedures call for PVC casing and a grout mix that closely matches the formation density. Basically, borehole preparation and completion procedures are the success or failure of crosshole seismic testing. Poor coupling between the casing and the formation yields delayed arrival times and attenuated signal amplitudes, particularly for (higher frequency) P-waves. Matching the formation density with a grout mix is not too difficult, but in open coarse-grained soils, problems arise during grout completion with losses into the formation. Even small grout takes begin to affect the velocity measured between two closely spaced drill holes. Several techniques to plug the porosity of the surrounding formation are commercially available (e.g., cotton-seed hulls, crushed walnut shells, or increased bentonite concentration in the grout mix). It should be recognized that increasing the ratio of bentonite/cement within the grout mix does affect density, but so long as the mix sets and hardens between the casing and in situ formation, quality crosshole seismic signals will be obtained.

(9) Another critical element of crosshole testing, which is often ignored, is the requirement for borehole directional surveys. There are several very good directional survey tools available which yield detailed deviation logs of each borehole used at a crosshole site. Borehole verticality and direction (azimuth) measurements should be performed at every depth interval that seismic data are acquired. With the deviation logs, corrected crosshole distances between each borehole may be computed and used in the velocity analysis. Since seismic wave travel times should be measured to the nearest tenth of a millisecond, relative borehole positions should be known to within a tenth of a foot. Assuming that the boreholes are vertical and plumb leads to computational inaccuracies and ultimately to data which cannot be quality assured.

(10) Recording instruments used in crosshole testing vary considerably, but there are no standard requirements other than exact synchronization of the source pulse and instrument trigger for each recording. Crosshole

measurements rely considerably on the premise that the trigger time is precisely known as well as recorded. The recorded trigger signal from zero-time geophones or accelerometers mounted on the downhole impact hammer allows accurate timing for the first arrival at each drill hole. This becomes uniquely critical when only two drill holes are used (i.e., source and one receiver) because there is no capability of using interval travel times; in this case, the velocity is simply determined through distance traveled divided by direct travel time. Utilizing digital recording equipment affords the operator the ability to store the data on magnetic media for analysis at a later date; but more importantly, digital data can be filtered, smoothed, and time-shifted during analysis. Also, digital signal processing may be directly performed for coherence, frequency-dependent attenuation, and spectral analysis.

(11) Numerous studies have shown that the effects on crosshole measurements by the choice of geophone is not critical to the results (e.g., Hoar (1982)). There are only two requirements for the receivers: the receiver (velocity transducer) must have a flat or uniform output response over the frequency range of crosshole seismic waves (25 to 300 Hz); and, a clamping device must force the receiver against the borehole wall such that it is not free-hanging. The clamping device should not affect the mechanical response of the geophone (i.e., resonance), nor should the uphole signal wire. If an SH-wave source is selected, then horizontal geophones must be used, and oriented as previously described, to detect the SH-wave arrivals. It is paramount that the polarity of each geophone be known prior to data acquisition because the direct arrivals of S-waves with reversed polarity can be easily misinterpreted. Hoar (1982) provides an excellent description of picking P- and S-wave arrivals off recorded crosshole signals. Hoar's dissertation shows that with proper borehole completion, digital recording equipment, and a preferential source-receiver system, clean reversed polarized and interpretable S-wave signals are relatively easy to acquire.

c. Interpretation.

(1) For interpretation of direct raypath travel times between two or three boreholes the Bureau of Reclamation (Sirles, Custer, and McKisson 1993) has published a computer program which is designed specifically for reducing crosshole seismic data. Furthermore, the program was fashioned around the ASTM conventions and test procedures outlined for crosshole seismic testing. The program CROSSIT (Version 2.0) is intended to be a step-by-step program that allows the user to:

(a) Input lithologic information obtained from geologic drill hole logs.

(b) Input deviation survey data for each drill hole.

(c) Input travel times for P- and/or S-wave arrivals at one or two receiver holes.

(d) Enter site-specific information (location, surface elevation, etc.).

(e) Map each borehole utilizing deviation survey information.

(f) Determine corrected crosshole distances between the respective drill hole pairs: source/receiver 1, source/receiver 2, and receiver 1/receiver 2.

(g) Compute direct P- and S-wave velocities from travel time data.

(h) Tabulate and/or graph (to hard copy or disk file):

- Borehole directional survey data and plots.
- P- and S-wave velocity depth profiles from each drill hole pair.

(i) Interactively edit input or graphical files and combine data sets.

(j) Post-process seismic data and/or plots for alternate uses.

(2) CROSSIT is built for compatibility with laptop or desktop computers and dot-matrix or laser-jet printers such that data reduction could be performed in the field as geophysical data are being acquired. The logic and flowchart for this interpretation and data presentation program are designed to follow the typical field data acquisition process (i.e., geologic information, borehole information, travel-time information) to permit interactive computer analysis during data collection. This technique of reducing data in the field has proven its value because of the ability to determine optimal testing intervals and adjust the program as necessary to address the site-specific problem.

(3) Unlike surface seismic techniques, crosshole testing requires a more careful interpretation of the wave forms acquired at each depth. For example, in crosshole testing, the first arrival is not always the time of arrival of the direct raypath. As illustrated schematically in Figure 7-46, when the source and receivers are located within

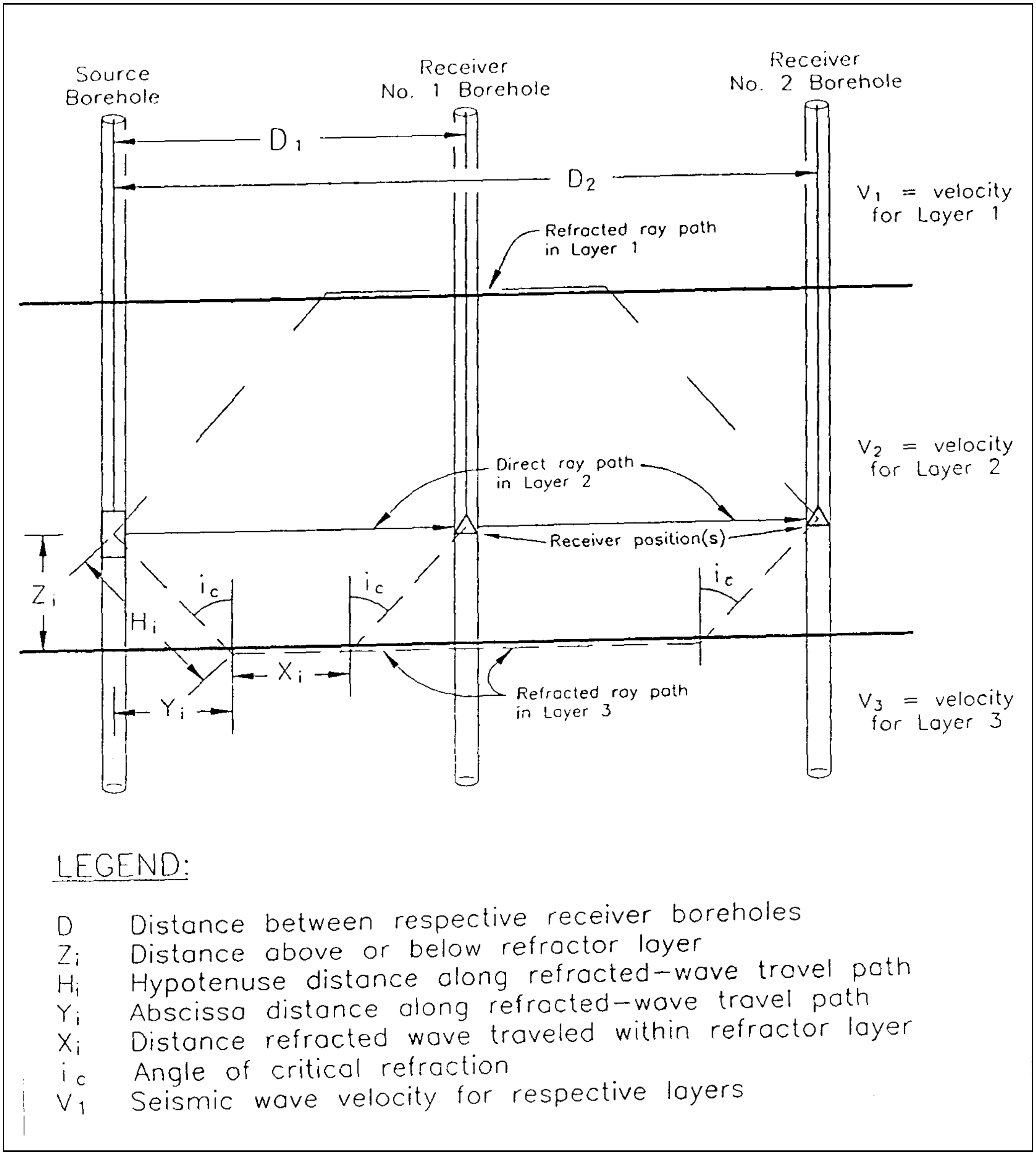


Figure 7-46. Illustration of refracted raypath geometries in crosshole seismic tests where $V_1 > V_2 < V_3$ and $V_1 < V_3$

a layer that has a lower velocity than either the layer above or below it (this is termed a hidden layer in refraction testing), refracted waves can be the first arrivals. Both the source/receiver distance above or below the high velocity layer and the velocity contrast (V_1 : V_2) across the seismic interface determine if the refracted wave will arrive before the direct wave. Due to the effect refracted waves have on crosshole data sets, ASTM procedures require a three-borehole array because velocity corrections can be made for refracted arrivals. Also, depending upon the velocity contrast across layer boundaries, direct arrivals through low-velocity layers are generally larger amplitude and thereby recognizable. This permits timing direct arrivals directly off the wave form. Figure 7-47 shows an example of (SV-) direct-wave arrivals and refracted-wave arrivals where the arrival time of the direct wave (slower) can be picked later in the wave form behind the low-amplitude refracted-wave arrival. In this example, refractions occur in a situation similar to that depicted in Figure 7-46; that is, refractions occur from high-velocity materials either above or below the low-velocity layer.

(4) When approaching seismic interfaces, refracted-wave arrivals begin to be timed as the first arrival which could (easily) be misinterpreted as direct-wave arrival. Therefore, the following sequence of eight steps (equations) will confirm detection of refracted-wave travel time or direct-wave travel time at each recording depth (ASTM 1984):

Compute i_c: $\sin i_c = V_1/V_2$

Compute hypotenuse distance H_i: $H_1 = H_2 = H_3 = Z/\cos i_c$

Compute abscissa distance Y_i: $Y_1 = Y_2 = Y_3 = Z\tan i_c$

Compute travel times through both materials:

$t_{V1} = 2H_1 / V_1$

$t_{V2} = (D1 - 2Y_1) / V_2$

[V_1 and V_2 are known from measurement above and below the seismic interface.]

Compute total refracted travel time: $T_{rfr} = t_{V1} + t_{V2}$

Compute total direct travel time: $T_{dir} = D_1 / V_1$

Retrieve measured crosshole travel time: T_{meas}

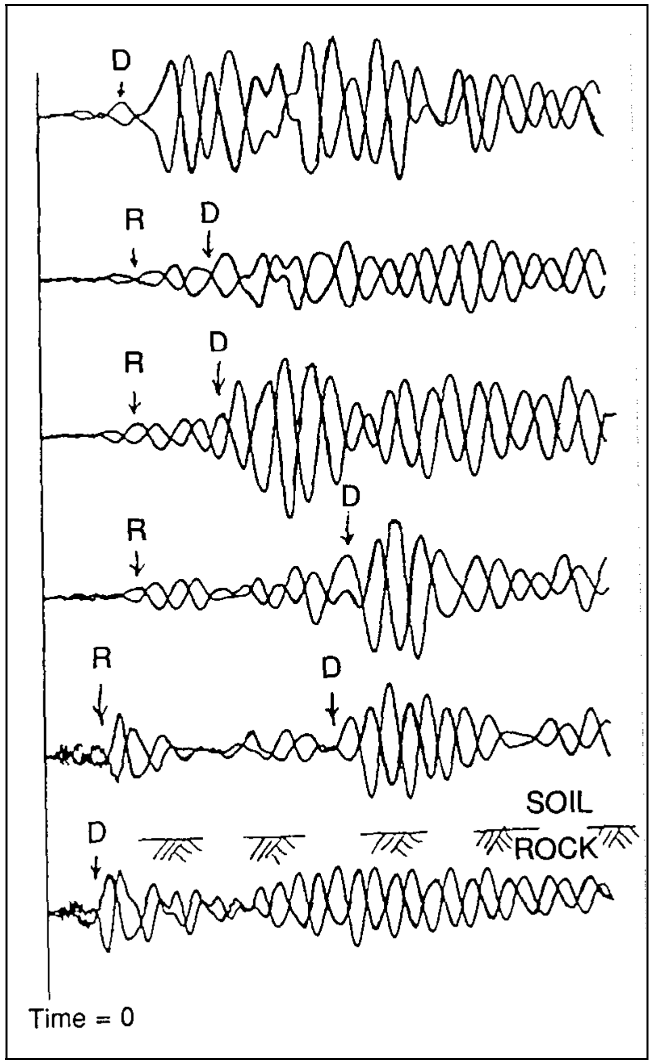


Figure 7-47. Crosshole SV-waves showing direct (D) and refracted (R) arrivals

Compare T_{rfr} with T_{dir} and T_{meas}:

IF: $T_{rfr} \leq T_{dir} \approx T_{meas}$ THEN: True V_1

IF: $T_{rfr} \geq T_{meas} < T_{dir}$ THEN: Apparent V_1 (refracted velocity)

(5) Comparing both sets of direct-wave velocities; that is, source to receiver No. 1 ($V_{(R1)}$) and source to receiver No. 2 ($V_{(R2)}$), with the interval velocity (V_I) computed from the following:

$$\text{Interval velocity} \equiv V_I = \frac{(D_2 - D_1)}{(T_{meas(R2)} - T_{meas(R1)})}$$

allows easy identification of boundaries with velocity contrasts. When V_I is much greater than the two computed direct-wave velocities, then refracted-wave arrivals are being timed as first arrivals at the second receiver borehole. Therefore, a systematic comparison of measured travel times, computed direct velocities, and interval velocities at each recording depth enables interpretation of true in situ velocity at all measurement depths. For crosshole tests, Butler et al. (1978) developed a computer program which performs this comparison of the respective computed velocities determined at every depth. Based on this discussion, to ensure that true in situ velocities are presented, crosshole measurements should be performed a minimum of four measurement intervals *below* the zone of concern to adequately define the velocity profile.

(6) The comparative technique for defining the refractor velocities outlined above assumes that the velocities are constant within each layer; however, occasionally this is an oversimplification. Some deposits have linearly increasing velocity with depth, primarily due to vertical pressures, where the apparent velocity for each depth can be computed with

$$V_{app}(z) = V_i + Kz$$

In these cases V_{app} is a function of depth (z), V_i is the initial velocity at zero depth, and K is the increase in velocity per unit depth. Direct-wave velocities computed for the far receiver (R2) at each depth will always be slightly higher than the near receiver (R1); hence, the interval velocity will be even higher. Increasing velocity with depth implies the seismic raypath is nearly circular between source and receiver thereby sensing deeper (higher velocity) material as the source-receiver separation increases. The effect of increasing velocity with depth is greatest within thick homogeneous soil deposits. In these soil conditions, computing an average velocity from the two direct velocities (i.e., $V_{ave} = (V_{(R1)} + V_{(R2)})/2$) is often the best estimate for presenting the in situ velocity profile.

d. Modelling and data processing.

(1) Typically, either forward or inverse modeling for cross-borehole seismic investigations consists of computing synthetic travel times to test the raypath coverage and resolution of either unknown or identified velocity anomalies, respectively. For engineering applications there is not much advantage in determining (via modeling) the ray coverage or residual velocity resolution because crosshole testing at the engineering scale utilizes a simple horizontal, straight-raypath geometry to determine average velocity. Also, lithologic information such as stratigraphy and material type are determined from the drilling and sampling program prior to seismic data acquisition; this allows reliable constraints, or boundary conditions, to be placed on the field data along the boundaries of the material between the boreholes.

(2) For engineering applications, digital signal processing in crosshole seismic tests is, similar to modeling, of minimal value. This, of course, assumes field data are acquired properly and no analog filtering or digital aliasing was performed prior to recording seismic data from each depth. There are a number of digital signal processing techniques useful for determining material properties other than P- or S-wave velocity, as well as confirming the computed crosshole velocity profile, such as:

(a) Spectral analysis for determination of inelastic constants (attenuation and/or material damping).

(b) Frequency analysis for correlation of phase and group velocity.

(c) Cross-correlation of recorded seismic signals from one receiver to another receiver borehole, or source to receiver coupling for signal coherence.

(3) Sophisticated processing is rarely required in (engineering) crosshole testing and the straightforward distance/travel time relationship for velocity computations is considered functional and effective.

e. Advantages/disadvantages.

(1) Crosshole seismic testing has the unique advantage of sampling a limited volume of material at each test depth. Thus, the final result is a significantly more detailed and accurate in situ seismic (P- and/or S-wave) velocity profile. Crosshole tests are not unique in the use of preferential source/receiver configurations; however, there is the distinctive opportunity to generate and record only body wave energy, as well as preferentially excite particle motion in three directions with respect to the vertical borehole wall. Because of this, the crosshole test permits much easier interpretation of direct arrivals in the recorded wave forms. Because boreholes are required there is the opportunity to obtain more site-specific geotechnical information which, when integrated with the seismic data, yields the best assessment for the engineering application (liquefaction, deformation, or strong motion characterization). Also, because each drill hole was cased for the crosshole tests, additional geophysical surveys should be conducted. Typically, geophysical borehole logging will be conducted in each drill hole for

the purpose of defining lithologic and stratigraphic continuity of the deposits.

(2) Crosshole seismic testing has the definitive advantage of assessing a complex layered velocity structure with alternating high and low relative velocities. Other surface techniques such as spectral analysis of surface waves can theoretically evaluate the high/low layered velocity structure, but due to a number of inherent assumptions associated with surface geophysical methods several non-unique velocity profiles may be derived (from inverse modeling) without specific information about the subsurface layering at the site. Since considerable confidence can be placed on engineering scale crosshole seismic data, computation of in situ low-strain elastic constants (Shear and Young's modulus, Poisson's ratio, etc.) permits dependable assessment of geotechnical parameters for the site-specific evaluation. Recently, sites of particular concern for obtaining P- and S-wave velocities are liquefaction studies where the subsurface contains considerable unconsolidated coarse-grained material and standard geotechnical test procedures (blow counts and material sampling) cannot effectively evaluate in situ properties. For successful engineering analysis of coarse-grained materials, crosshole testing is one of the most acceptable geophysical techniques available.

(3) The primary detriments or obstacles encountered during crosshole testing are typically related to the placement and completion of multiple drill holes. Sites where noninvasive techniques are required due to hazardous subsurface conditions, crosshole seismic tests are not applicable because of tight regulatory procedures regarding drilling, sampling, and decontamination. However, at sites where detailed in situ P- and S-wave velocities are required, drill hole completion must follow ASTM procedures, and when unusual conditions exist (e.g., open-work gravels) specialized techniques for borehole completion should be employed. The U.S. Bureau of Reclamation has encountered numerous sites in the western United States where loose, liquefiable sand and gravel deposits needed to be investigated and crosshole testing effectively evaluated the in situ material density and stiffness with P- and S-wave velocities, respectively; but considerable care and caution were used for completion of each borehole (U.S. Bureau of Reclamation 1992).

(4) Seismic data for crosshole testing need considerably more wave form interpretation because refraction events from high-velocity layers either *above or below* a low-velocity layer must be identified and the first-arrival velocity corrected. Direct-wave arrivals are easily recognized (even with low-amplitude refracted arrivals) as long as the previously described field equipment is utilized for preferential generation of P-waves or polarized SV or SH-waves. The ASTM requirement of three drill holes seems costly to a project budget; however, the necessary source/receiver configurations and borehole separation allow optimal correction and evaluation of in situ P- and S-wave velocities for each material layer at depth.

f. Sample problem.

(1) To illustrate the effect of a high S-wave velocity layer overlying a low S-wave velocity layer on crosshole wave forms, the following sample problem is presented using data acquired at a site in central Utah. Figure 7-48 shows a portion of the wave forms collected over the depth interval 17.5 to 32.0 m, as well as the entire S-wave velocity profile obtained at this site. Only one polarity of the S-waves obtained is plotted over this depth interval (unlike the opposite polarity data shown in Figure 7-47), but the arrival of the S-wave is clearly distinguished from the lower-amplitude and higher-frequency P-wave arrival.

(2) The objective of this investigation was to determine if a low-velocity alluvial layer exists beneath the embankment, which was constructed in 1943. Data are then used to determine the liquefaction potential of the foundation alluvial deposits. As clearly shown on the sample problem figure, directly beneath the embankment the velocities decrease to less than 240 m/s in a layer of lean clay, which is not considered liquefiable; however, within the silty sand alluvial deposits, the wave forms show considerable increase in the S-wave travel times, and the computed velocities indicate potentially liquefiable deposits with S-wave velocities less than 180 m/s (600 ft/s). Beneath approximately 30 m (90 ft) the S-wave velocities gradually increase to greater than 240 m/s.

(3) This sample problem, or example data set, illustrates three distinct advantages that crosshole testing has over conventional surface geophysical testing for these types of investigations:

(a) Ease of identification of direct arrival S-waves.

(b) Ability to determine the presence of low-velocity materials (alluvium) directly beneath high-velocity materials (embankment).

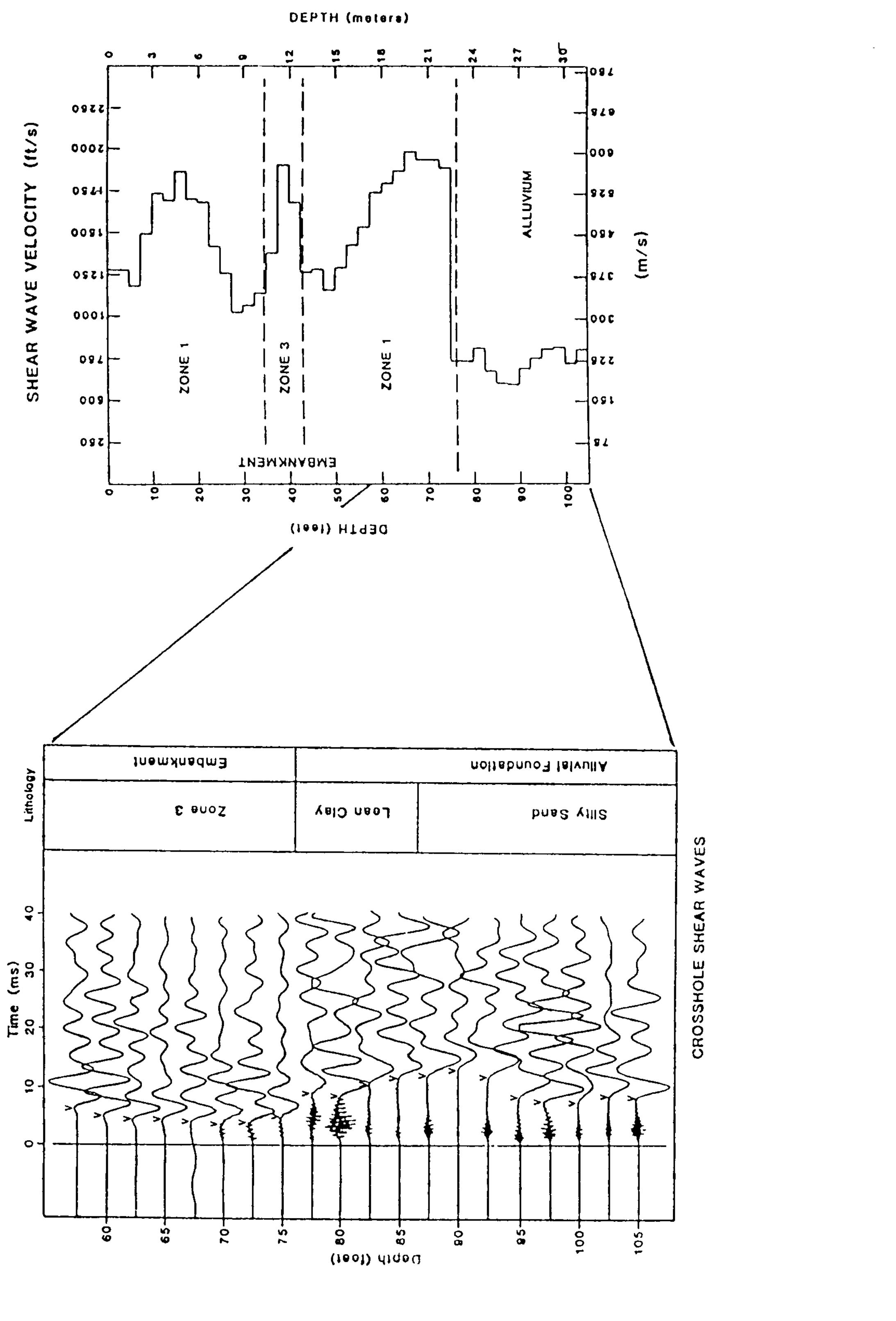


Figure 7-48. Example problem

(c) Direct and fairly straightforward computation of the S-wave velocity profile, which is correlated with the liquefaction potential of both the materials and depth intervals of engineering concern for the safety of the structure.

7-3. Surface to Borehole Procedures

a. Overview of borehole seismic methods. There are fundamental physical reasons why borehole seismic techniques can provide potentially better answers than conventional surface seismic techniques. There is a progression in both complexity and benefits from check shot and synthetic seismogram to vertical seismic profiles (VSP), three-component VSP, offset VSP, and extrapolation and description of lithologic parameters into the geologic formations surrounding the borehole. Presently VSP's are run in wells to aid in the correlation of surface seismic data. Borehole velocity surveys, commonly called *check shot surveys*, are often expanded into VSP's since additional acquisition costs are relatively small.

(1) Synthetic seismograms. Synthetic seismograms have traditionally been used to correlate surface seismic sections. Like all theoretical models, synthetic seismograms suffer from the simplifying assumptions that go into the model. An approximate fit to surface seismic lines is often obtainable. However, synthetic seismograms offer an important link in trying to understand the seismic tie to the well log. An example of a synthetic seismogram is shown in Figure 7-49.

(2) Velocity surveys. Velocity or check shot surveys are well established in the geophysical community. Sources and receivers are distributed to obtain vertical travel paths through the formation of interest. Receivers are placed at or near geological horizons of interest. On the recorded seismic trace, only the information from the first arrival is used. A velocity survey field setup and recorded field data are illustrated in Figure 7-50.

(3) Time-depth plots. Seismic first arrivals are converted to vertical travel times and plotted on time-depth graphs. The time-depth information is used to calculate average, root-mean-square, and interval velocities.

(4) Sonic log calibration. Sonic log calibration is one of the applications of velocity surveys. Velocity obtained from sonic logs can be affected by a variety of borehole effects. Integrated sonic logs are subsequently distorted by these borehole effects. The resultant discrepancy between seismic and sonic measurements, called drift, must be corrected prior to the construction of synthetic seismograms to prevent the shifting in time of the seismic reflections or the introduction of pseudoevents.

(5) Vertical seismic profiles. In vertical seismic profiling full use is made of the entire recorded seismic trace, in addition to the first break. Receivers are spaced at close intervals throughout most of the wellbore in order to obtain a seismic section of the wellbore. The seismic wave itself and the effects on it, as it propagates through the earth, are measured as a function of depth. Receivers are now close to reflectors. In addition, both upgoing and downgoing wavefields are recorded at each receiver. The downgoing wavelet with its reverberant wave train is observed as a function of depth and can be used to design deconvolution filters. Signal changes in terms of bandwidth and energy loss can be measured. In general, the VSP also provides better spatial and temporal resolution. Figure 7-50 illustrates the generation and travel paths of direct arrivals, reflected primaries, and examples of upgoing and downgoing multiples.

(a) Vertical seismic profiling permits correlation of the actual seismic event inclusive of all the changes it undergoes, multiples, attenuation, etc., at the actual recorded depth. This leads to a great deal more confidence in correlating surface seismic profiling. An example of correlation between VSP and surface seismic profiling is shown in Figure 7-51.

(b) Resolution in vertical seismic profiling is generally much improved over that obtainable with conventional surface seismic profiling. This is largely the result of the shorter travel path. With VSP's, high-resolution mapping of, for example, a reservoir can be accomplished. Better estimates of rock properties, including below the bit, can be obtained.

(c) The information from the VSP about multiples and signature attenuation can be used to upgrade the processing of surface seismic profiling. In fact, it is anticipated that reprocessing of surface seismic profiling will be done routinely when good VSP data are available.

(d) The inversion of seismic traces from VSP data to predict impedance changes below the drill bit has been demonstrated with remarkable success. This is largely because careful matching of impedances in the known portion of the drillhole has led to increased reliability when predicting below the bit. A popular application is that of predicting overpressure zones. Details of the technique will be discussed under VSP applications.

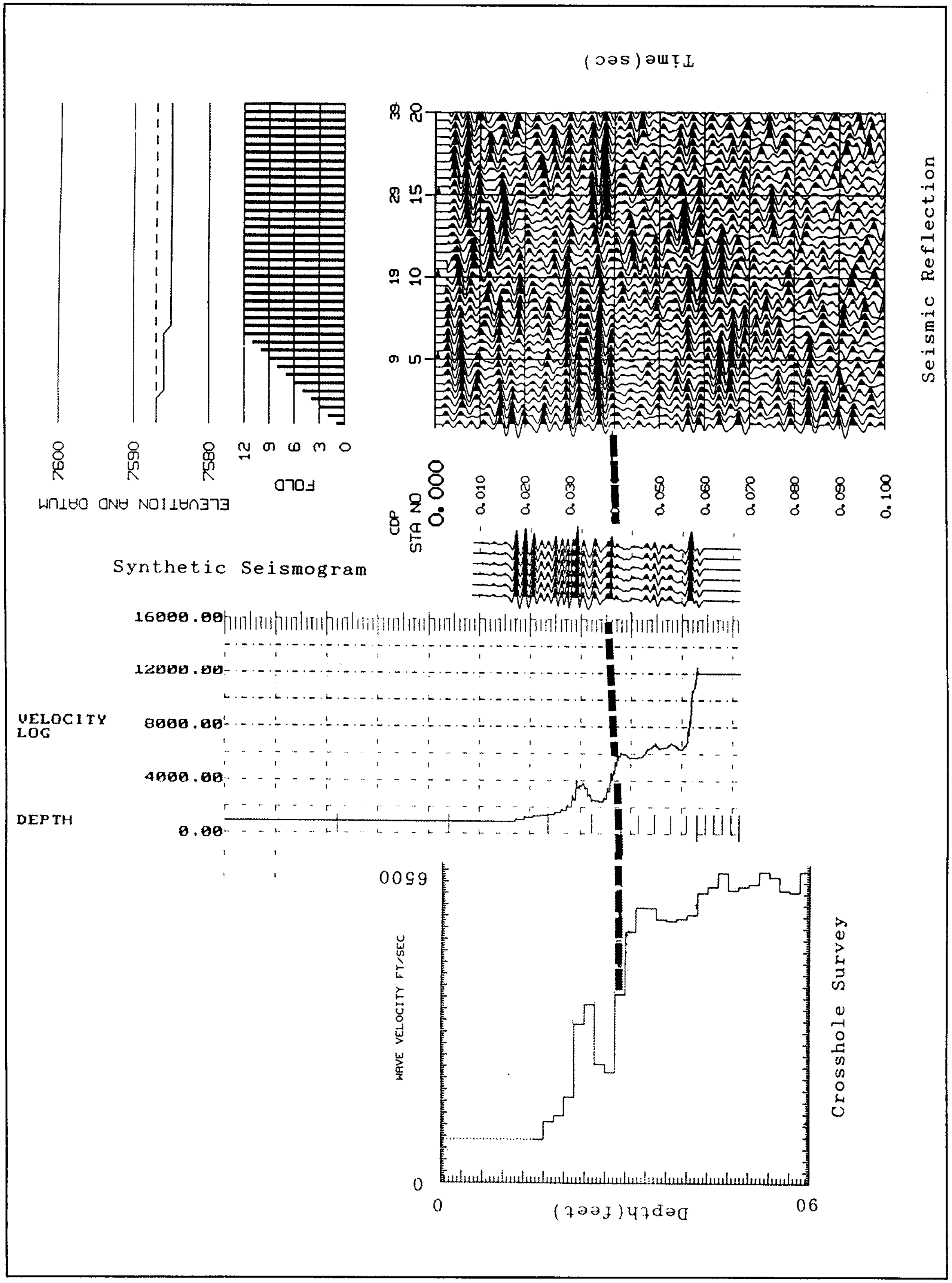


Figure 7-49. Correlation between crosshole survey, velocity log, synthetic seismogram and surface seismic reflection section

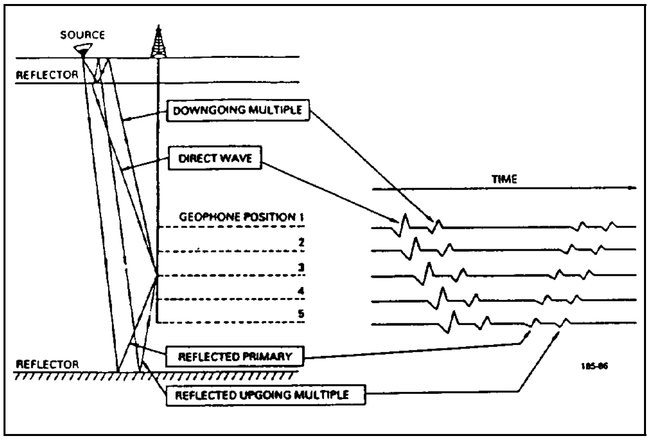


Figure 7-50. Recording of a vertical seismic profile; direct arrivals, reflected primaries, and examples of downgoing and upgoing multiples are shown on the right

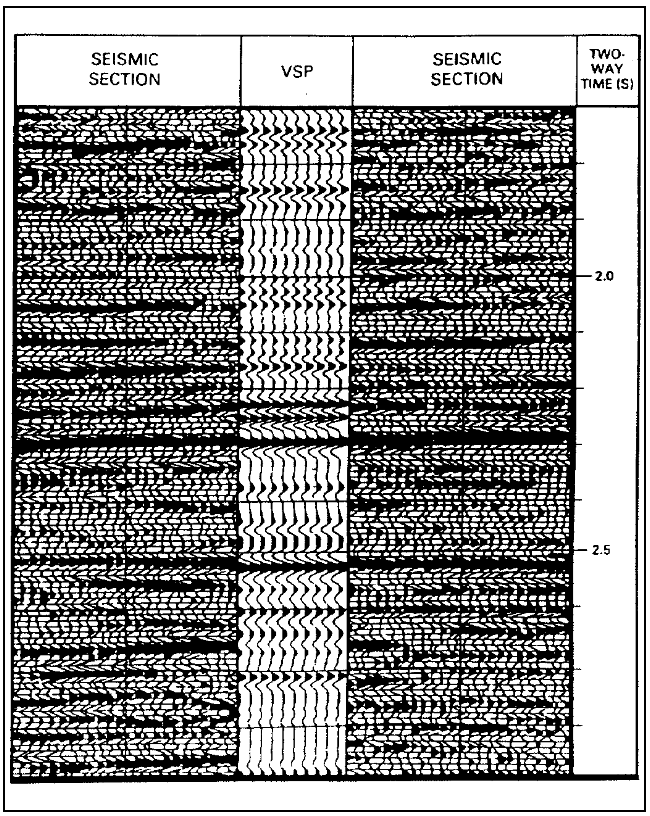


Figure 7-51. Example of correlation between VSP and surface seismic profiling; the VSP data stack is shown at the proper well location with respect to the seismic section

(e) Offset VSP's were developed to illuminate structure away from the wellbore. Applications are primarily to find faults and pinchouts. An example of an offset VSP is shown in Figure 7-52. The top left shows a fault model. The top right shows a synthetic VSP with the typical break in the upgoing primary reflection due to faulting.

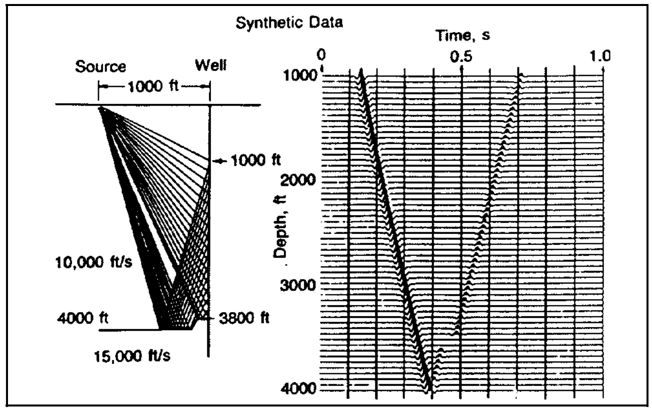


Figure 7-52. Model of fault structure

(f) Multiple offset or walkaway VSP's were developed to supply high-resolution seismic structural detail or provide seismic data in areas where interference from shallow layers all but renders surface seismic profiling useless. Notable improvements have been observed in some no-record seismic areas. Lateral extension of structural and stratigraphic detail around the wellbore is made possible with this type of survey.

(g) VSP's can be obtained around each well in a multiwell project to help map the geology. Careful correlation can be accomplished with existing 2-D and 3-D surface seismic profiling. Finally, the entire sequence of formations of interest may be mapped in terms of porosity, saturation, permeability, etc., by carefully calibrating VSP data with well log data.

(6) Downhole sources. Downhole sources such as explosives, implosive devices, airguns, and sparkers are economically desirable, and a great deal of research has gone into making them successful. Downhole sources suffer from a bad reputation concerning wellbore damage. Data from a number of experiments show that borehole-generated events associated with downhole sources tend to overwhelm data quality to the point of turning this technology into an interpretational problem.

(7) Downhole receiver arrays. Downhole receiver arrays of only a few geophone receiver elements have been used successfully and have greatly reduced acquisition costs in borehole seismics. Downhole hydrophone

arrays have been used commercially to measure permafrost thickness. An interesting application of hydrophone arrays was the successful measurement of tube waves generated by permeable fracture zones in granite.

b. Velocity surveys.

(1) Introduction. Velocity surveys in well bores are a well established technology in the geophysical industry. An accurate measurement of the travel time and depth location, in combination with a knowledge of travel path, will provide the geophysicist with the necessary velocities to convert the seismic time sections to depth and also to migrate the data properly.

(a) Sonic logs provide this data also; however, sonic logs are usually run only to surface casing. Tying the information from the sonic log to the surface requires a velocity or check shot survey. Usually, enough levels are obtained in the wellbore to provide sufficient detail to forego the data obtained from the sonic log.

(b) In the section on overview of borehole seismic techniques some problems that can affect sonic log data accuracy were discussed briefly. Seismic travel times are considered accurate within the limitations of sample rate and first break picking accuracy, and sonic times must be adjusted to fit the seismic data.

(2) Field technology. Sources for data acquisition must be carefully chosen for the given desired depth penetration. These sources may include explosives, airguns, or water guns in containers, or vibrators. Source and acquisition parameters often tend to match those used during acquisition of surface seismic data.

(a) Receivers are downhole geophones. A more detailed discussion of source and receiver characteristics will follow in the section on vertical seismic profiling.

(b) In locating the source, an attempt is made to obtain a travel path that minimizes refractive bending through the formations. For the case of horizontal layering and a vertical well, that would imply placing the source close to the well bore. For a deviated well, the source is frequently moved above the receiver in the well. This, of course, requires information from a well deviation survey prior to the check shot survey. Dipping layers can also introduce sizeable changes in travel time because of refraction along bed boundaries.

(c) When working with surface sources such as vibrators, it is advisable to obtain some shallow levels in order to get some information on velocities in the weathered zone. The limitation in this case is the source location, since the drilling platform itself may take up a sizeable space. In addition, refracted arrivals from the top of the subweathering zone or casing may interfere with direct arrival through weathering.

(d) When working with explosives, an uphole high-velocity geophone is needed to obtain the uphole times. Proper shot depth with the uphole time can provide the information on weathering velocities. Shot holes are generally located some distance from the wellbore to prevent wellbore damage. Therefore, in this case shallow levels in the borehole may not add much to the survey.

(e) Some comments are in order concerning the placements of geophones in the borehole. Often geologists pick recording depths corresponding to formation tops obtained from logs. If acoustic boundaries of sufficient contrast are in that vicinity, interference between direct and reflected arrivals may lead to errors in first arrival times. Better receiver locations can sometimes be picked below the horizon of interest from existing sonic logs. Another effect may include the gradual polarity reversal of the first break.

(f) If receiver spacing is too close, there may be sizeable errors in computed interval velocities. In this case the picking of the first break is rarely more accurate than 1 ms. With a receiver spacing of, for example, 30 m and a velocity of 3,000 m/s, a 1-ms error would amount to a 10-percent error in the computation of velocities.

(3) Data reduction. When converting travel times to vertical travel times, a straight line path is normally assumed. This is shown in Figure 7-53. Refinement of the results can be obtained by modeling and using the initial straight raypath as a first guess. For a vertical well the horizontal distance from the source to the well and the vertical distance from the source to the geophone in the well are used. For the deviated well, the horizontal distance from the energy source to the geophone is used in addition to the vertical distance. The azimuth of the energy source is required when corrections for deviations are required. For offset or walkaway shooting, where the source is moved, the coordinates must be known for every shot.

(a) All computations are corrected to the seismic reference datum (SRD). These corrections are summarized in Figure 7-54. Finally, the corrected computations are displayed in the familiar time-depth plot shown in Figure 7-55. This graph also provides an opportunity for

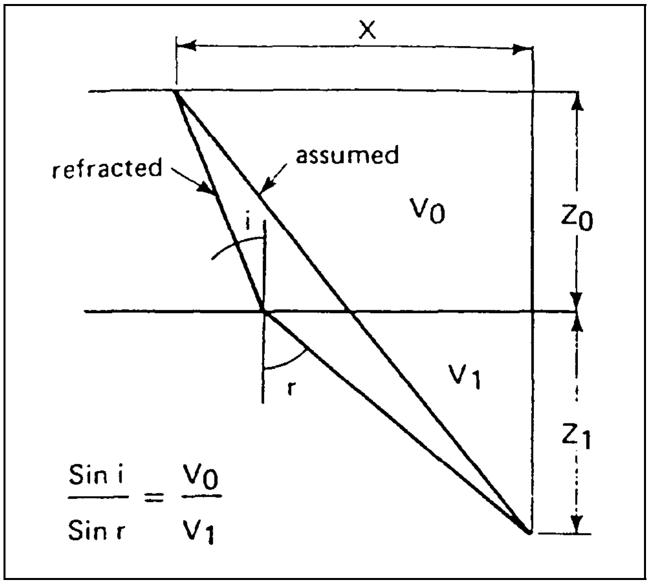


Figure 7-53. Travel path used for converting total travel time to vertical travel time

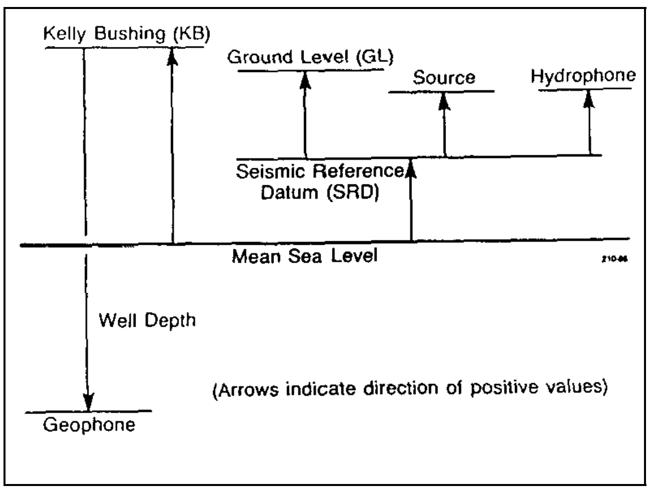


Figure 7-54. Summary of possible corrections to tie velocity survey to surface seismic data

quality control. Points deviating greatly from the trend may require a more detailed evaluation.

(b) Results of the velocity or check shot survey are used to tie time to depth and calculate average, interval, and RMS velocities (see Figure 7-56). These velocities are used to study normal moveout (NMO) in data migration and are often used to correct sonic logs prior to the computation of a synthetic seismogram.

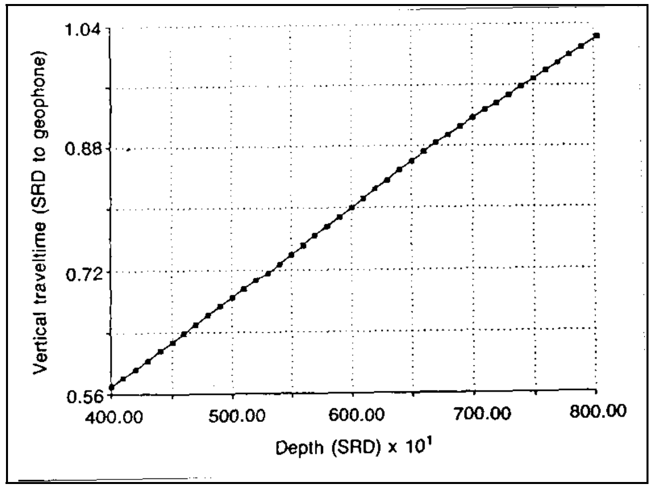


Figure 7-55. Vertical time-depth plot corrected to SRD

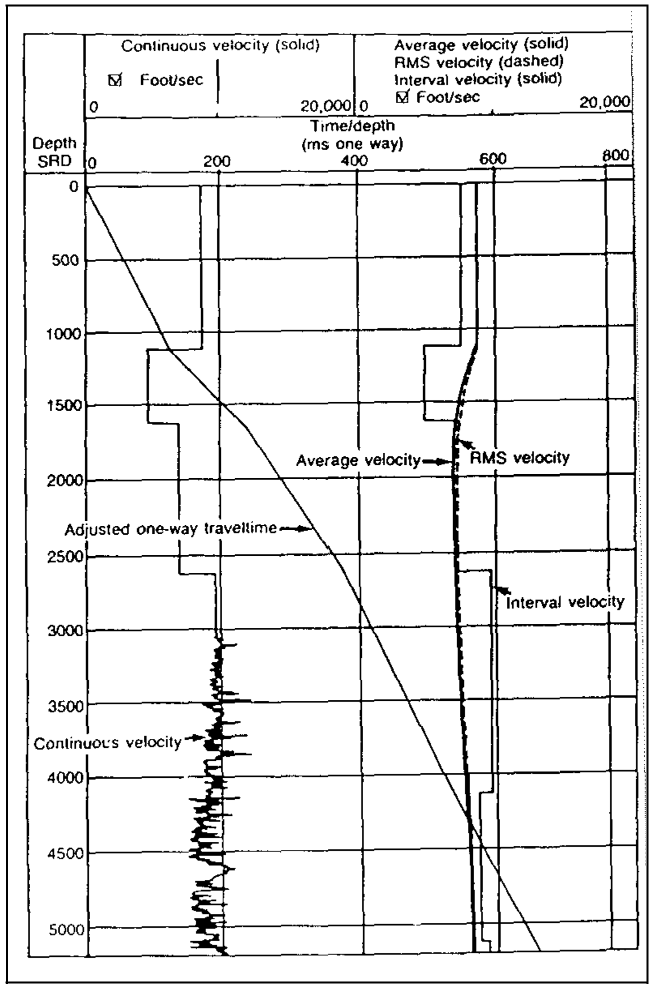


Figure 7-56. Example of final display from velocity survey shown with sonic log

c. Vertical incidence VSP.

(1) Introduction. Vertical seismic profiling has been one of the more rapidly developing technologies in geophysics in recent years. It is perhaps surprising that the information following the first breaks on the seismic trace routinely recorded in velocity surveys was simply disregarded. Acquisition in the field for VSP's consisted then merely of the addition of a sufficient number of geophone depth levels in a routine velocity survey. The additional rig time was perhaps the major deterrent to the widespread use of VSP's in the industry.

(a) The geophysicist had also settled for the use of check shot surveys and synthetic seismograms to provide him with a more or less accurate nexus between surface seismic profiling and the well bore. This meant accepting all the assumptions of plane acoustic waves striking a horizontally layered medium at normal incidence to obtain a model of a seismic trace arriving at the surface. Another shortcoming was the lack of knowledge of the makeup of the seismic wavelet.

(b) The VSP permits the actual measurement of seismic energy as a function of depth. The surface geophone measures only the upgoing wave. The downhole geophone measures the downgoing wave field in addition to the upgoing wave field. Effects of reflection, transmission, multiples, and attenuation can be traced as a function of depth. The increase in resolution resulting from retention of higher frequencies (due to the decrease in travel path to the downhole geophone compared to a surface geophone) permits more confident measurement of lithological effects than ever before from surface seismic profiling. The advent of shear-wave seismic technology has brought with it the difficulty of resolving both P- and S-waves to the same lithologic boundary. Again, the VSP can provide an accurate tie between these two events. Finally, the VSP is one of the more effective means to provide quality control for both surface seismic profiling and the generation of a reasonable synthetic seismogram. As the geophysicist gains experience with VSP acquisition, processing, and interpretation, this relatively new technology will become an integral part of exploration technology.

(2) Principles. Simultaneous recording of both upgoing and downgoing wave fields by the downhole geophone requires some discussion of the principles involved. In Figure 7-57(b), examples of some possible upgoing and downgoing events are displayed. For convenience and clarity, upgoing events are to the left of the well, downgoing are to the right. Furthermore, only two geophone locations are shown, again separated for convenience in illustrating the concept. In reality more events than those shown are possible. Figure 7-57(a) is the simple impedance model for this hypothetical well. Figure 7-57(c) shows the VSP generated from this model as a function of the depth of the well versus one-way time.

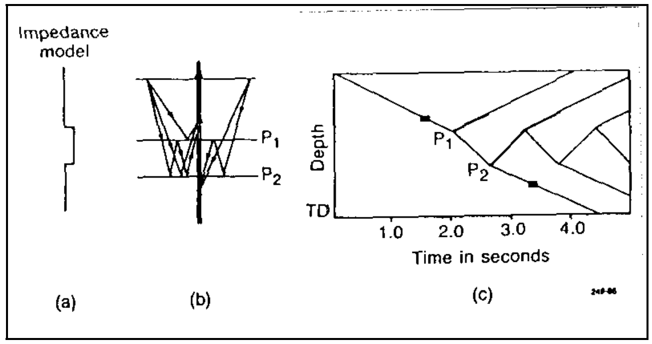


Figure 7-57. Basic concept of upgoing and downgoing wave fields, (a) Impedance model, (b) Ray geometry, (c) VSP

(a) The upgoing events shown consist of two simple primary reflections and one multiple. The downgoing events shown consist of the direct arrival and one downgoing multiple. In Figure 7-57(c), the first arrivals are on the left-most line increasing in time with depth; i.e., from upper left to lower right. Changes in slope on this line indicate changes in velocity in the subsurface. Primary upgoing events (P1,P2 in Figure 7-57b) intersect this line of first arrivals and proceed towards the upper right on the graph.

(b) In zero-offset VSP's, the primary events are symmetric to the first arrivals and together with the first arrivals have typically a "V" shape. Primary reflection P1 illustrates the time-depth tie necessary for correlation.

(c) The diagram shows the important fact that upward-travelling multiple events cease as soon as the geophone is located below the last reflector involved in its generation. The primary reflection and all the multiples in its tail have their last bounce on that reflector; hence, when the geophone is below that reflector, primary and upgoing multiple reflections in the tail can no longer be recorded. This multiple, or reverberant, is henceforth only present in the downgoing wave below this point. Upgoing events that terminate within the data permit the recognition of the origin of a multiple.

(d) A real VSP is shown in Figure 7-58. Data have been corrected for amplitude losses. The traces are arranged with depth increasing from top to bottom and time increasing to the right; hence, longer travel times to the first arrival are seen with increasing depth. One should note the sparsity of strong upgoing events and the usual predominance of downgoing multiple events from near surface highly reverberant systems. When lowering the geophone, a downgoing multiple event will be delayed by the same additional amount as the primary event. As a result, in the case of horizontal layering, the whole family of multiples follows but remains parallel to the first arrival alignment. This fact will subsequently be exploited in the processing of the vertical incidence VSP. The first arrivals then draw the time-depth curve. As the geophone moves further from the source, it moves closer to the reflector; hence, the additional delay from source to receiver is equivalent to an identical loss in travel time from reflector to receiver in horizontal layering. As a result, reflected arrivals slope in the opposite direction from first arrivals.

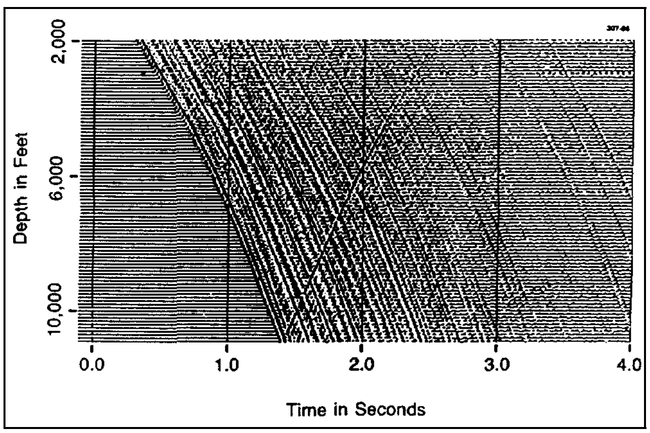


Figure 7-58. Example of a VSP recording in one-way time with gain correction applied

(3) Synthetic VSP's. The synthetic VSP is rapidly becoming a valuable aid in studying the behavior of upgoing and downgoing wave fields with acoustic impedances obtained from borehole logging. Whereas the synthetic seismogram models a layered earth as seen from the surface, the synthetic VSP is a study of seismic events as a function of depth. It also allows the interpreter of VSP's to gain a better understanding of the complexities of interacting wave fields and gives more confidence in interpretations.

(a) In calculating synthetic VSP's, one should incorporate the various multiple events. Upward-travelling multiples are reflected an odd number of times, downward-traveling multiples are reflected an even number of times (see Figure 7-57). For upward traveling multiples, a so-called first order multiple would have been reflected three times, a second order multiple five times, etc. By analogy, a first-order multiple for downgoing waves has been reflected twice, etc. (see Figure 7-57).

(b) For a synthetic VSP, the earth model is divided into equal travel time layers. The total seismic response for the layered system can be computed from the individual contributions of upgoing and downgoing waves at the individual interfaces for all the layers in the model. Multiples up to a given order can be included with overall attenuation as a function of reflection losses. The proper choice of input wavelet again becomes important if one attempts to match a synthetic with a real VSP. It is noted that the real VSP may be contaminated by random and coherent noise, difficult to reproduce with a synthetic. In order to illustrate the principles and the effects illustrated above, a simple model and the synthetic VSP calculated from it are shown in Figure 7-59 (Wyatt 1981). The velocity contrasts in the model are rather large in order to accentuate the effects discussed above. Velocities are seen to range from 1,500 to 6,100 m/s (5,000 ft/s to 20,000 ft/s). Density was held constant.

(c) Real VSP's rarely show multiple events that clearly. The first arrival slopes in this model show the velocity changes clearly. Amplitudes of primary events give a good indication of the impedance contrast at the boundaries. Amplitudes also show how a shallow reverberant system gives rise to many strong multiples. The origin of multiples is also clearly visible on this synthetic VSP. An excellent example of a comparison between a synthetic and a real VSP is shown in Figure 7-60. Coherent noise interference for the example is seen between 5,500 and 6,000 ft on the real VSP. Differences in primary and multiple amplitudes are also very much apparent. Synthetics then become a valuable aid (but not a replacement) for measuring true wave forms in the earth.

(4) Survey sources and equipment. Selecting a source for a VSP survey is largely a function of what was used in obtaining surface seismic data. For improved matching of VSP and surface seismic data, the same sources are desirable for both surveys. To date the majority of seismic data are collected with vibrators, airguns, and explosives. However, a number of other devices have appeared on the market and some familiarity with signal strengths and source characteristics is desirable. A great deal of care must go into the choice of sensors and

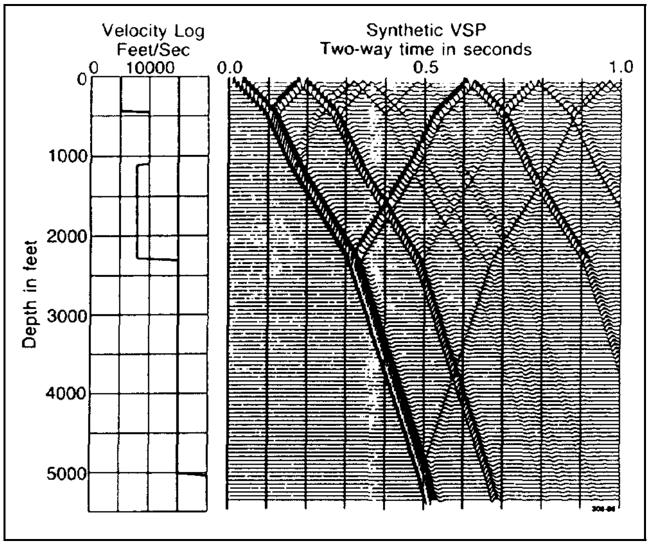


Figure 7-59. Simple synthetic VSP illustrating effects of multiples

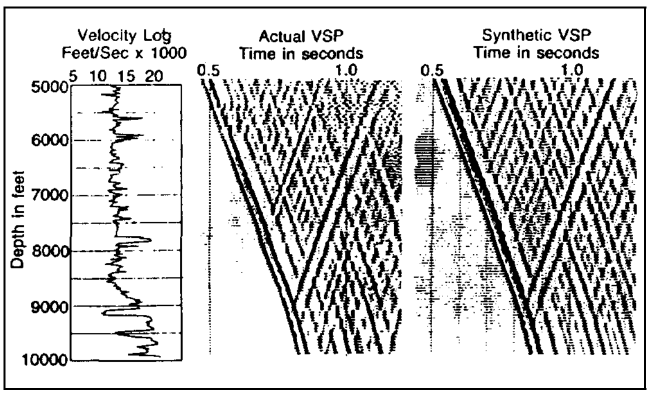


Figure 7-60. Comparison of real and synthetic VSP's

recording equipment. In VSP work, demands on recording equipment and the number of sensors employed are much smaller than in surface seismic operations. Recording equipment may have as few as two channels for single-axis tools. Downhole sensors may have only a single geophone per axis with three-axis tools. Downhole geophone tools require a clamping mechanism. Data for VSP's and check shots have been collected both with geophones and hydrophones in the downhole environment for specific applications.

(5) State-of-the-art technology.

(a) State-of-the-art geophones may be used in downhole seismic data acquisition. A variety of choices are available in the marketplace. As a starting point in downhole tool evaluation the geophysicist should know the amplitude and phase response of each type of geophone used in the tool. This is of increased importance when considering the differing response characteristics of vertical and horizontal geophones used in the three-axis tools.

(b) Additional complications are introduced by geophone-to-ground or formation coupling. Seismic phase and amplitude are highly distorted upon approaching resonant frequencies. The useable seismic frequency band must then remain well below the frequency peaks introduced by coupling to the formation. These formation coupling effects do exist in the borehole. Here the geophone becomes part of the larger downhole tool, which can, in combination with the formation, give rise to formation coupling resonances. In practice this is mostly experienced with horizontally oriented geophones. With presently available commercial tool designs, coupling resonances have been observed to fall into a frequency range as low as 18 to 30 Hz.

(6) Borehole seismic operations.

(a) For borehole seismic operations, conventional surface seismic systems are more than adequate for most applications. The requirement of only a few channels simplifies the field acquisition. Adjustable fixed downhole gain is most certainly desirable to prevent overdriving of the surface amplifiers by direct arrival.

(b) With continued interest in shear-wave data from three-axis VSP's and large S-wave sources, shear-wave attenuation rates amount to twice the decibel loss of that experienced by compressional waves. Adding attenuation losses from spherical divergence, scattering, and transmission losses would quickly tax the dynamic range of most recording equipment except for rather low frequencies.

(7) Planning. From the preceding sections it has become apparent that more than casual job planning is required to obtain good field data. A variety of additional field parameters are to be determined prior to venturing out into the field. Rig time and source expense often lead to a series of compromises concerning sources, and number of levels obtained in the well. Source offset may be a function of desirable noise suppression of tube waves. Shallow levels are often noisy.

(8) Quality control.

(a) Quality control must extend to the borehole environment. Poor tool coupling may lead to tool creep or slippage. Improved clamping pressure, or perhaps installation of clamping arms or a more suitable length for a given borehole, will usually solve creep and slippage problems with their attendant noise bursts. Slacking off the cable eliminates cable waves in addition to reducing surface noises traveling down the cable. Tool resonance associated with poor coupling at a given location is solved by moving the tool to a different location. Both caliper and sonic logs may become helpful in relocating the tool.

(b) The effects of casing may lead to additional phenomena in VSP acquisition. Refracted casing arrivals may precede direct arrivals. Unbonded casing may lead to casing ring. Cased hole VSP's can be obtained after the rig has moved off the site. This leads to a sizable savings in rig time during acquisition.

(c) The effect of tube waves in VSP recording is that of coherent noise. Tube waves can be generated by body waves impinging on the borehole or by surface waves crossing the borehole. Tube wave velocities typically come in at velocities of about 1,450 m/s . There are a number of field approaches to reduce tube waves. Improved clamping can greatly reduce tube waves. Another approach to reducing tube waves is source offset from the borehole. This is illustrated in Figure 7-61. Different sources give rise to sizeable differences in tube wave energy.

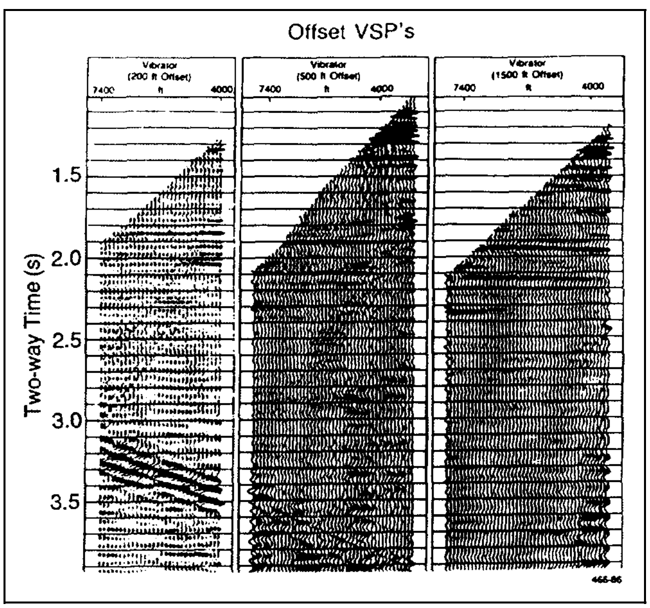


Figure 7-61. Tube wave amplitudes as a function of source offset

(d) With increasing experience in both data acquisition and processing, VSP can supply the additional refinements in seismic exploration that heretofore were elusive with surface methods. Data from the VSP can now help to solve a number of exploration problems and give the additional confidence often needed to solve interpretational ambiguities.

(e) In the past, direct correlation of synthetic seismograms with surface seismic profiling, however successful in some areas, led to a great number of unresolvable errors between well logs and surface seismic profiling. The synthetic seismogram, after all, is a theoretically calculated response based on some rather simple assumptions and as applied to logging data, is subject to all the various restrictions discussed in earlier sections. With the VSP one finally has a measured response of the earth to the actual source wavefield as it progresses with depth. A connection can now be established directly between seismic analysis and wellbore information. The synthetic then becomes a means to model and study seismic signal interaction with the details of formations rather than serving explicitly as a link to the well. A synthetic log is then relegated to serve to some degree as quality control in the design of VSP data acquisition in conjunction with ray trace modeling and synthetic VSP computations. A well tie that serves both the geologist and the geophysicist will typically include the display of time-scaled logs, synthetic log, corridor or sum stack, the VSP itself, and the surface seismic section. In addition, a VSP converted to an equivalent section by summing corridors of traces along equal offset distances from the wellbore may be included. A variety of displays can now aid the interpreter. Figure 7-62 shows the correlation from time-scaled logs to VSP to surface seismic. Shown from left to right are caliper, gamma ray, bulk density, sonic, reflectivity, synthetic log, corridor stack, VSP-CDP, and surface seismic data.

(9) Conclusions and examples.

(a) From the previous discussions on vertical VSP applications there are many benefits obtainable. Careful calibration of logs with VSP's and calibration of VSP's with surface seismic profiling can lead to much refinement in the interpretive process. Correlation of log-derived lithologic facies can be directly correlated with the results of seismic studies. To establish better communication between geologist, log analyst, and geophysicist, displays such as that shown in Figure 7-63 were developed. Additional calibration with logs and seismic profiling can be achieved by comparing data from seismic events to those obtained from logs. Amplitudes of reflection coefficients and seismic events may be correlated with more confidence to porosity, pore fluids, saturation, and lithology after proper calibration with logs.

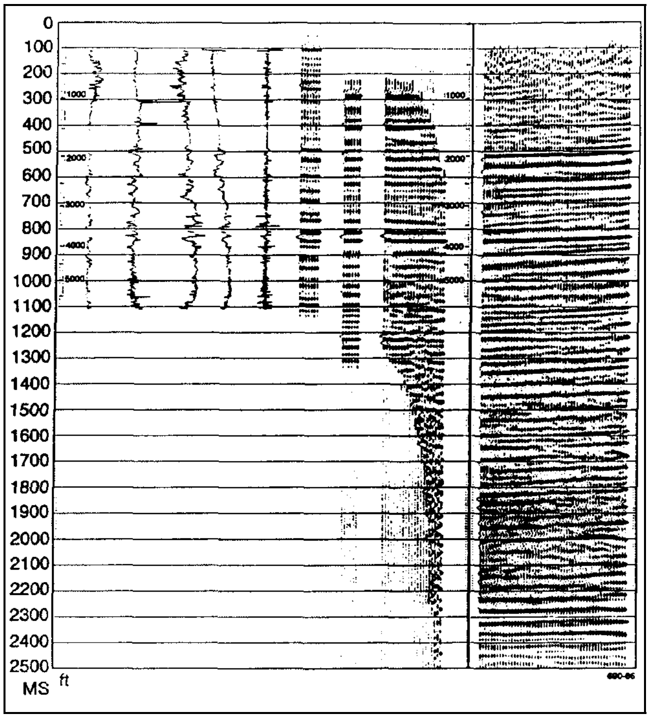


Figure 7-62. Correlation of time-scaled logs with VSP and surface seismic section. Shown from left to right: caliper, gamma ray, bulk density, sonic, reflectivity, synthetic seismogram, sum stack of near traces of VSP-CDP, VSP-CDP, surface seismic section

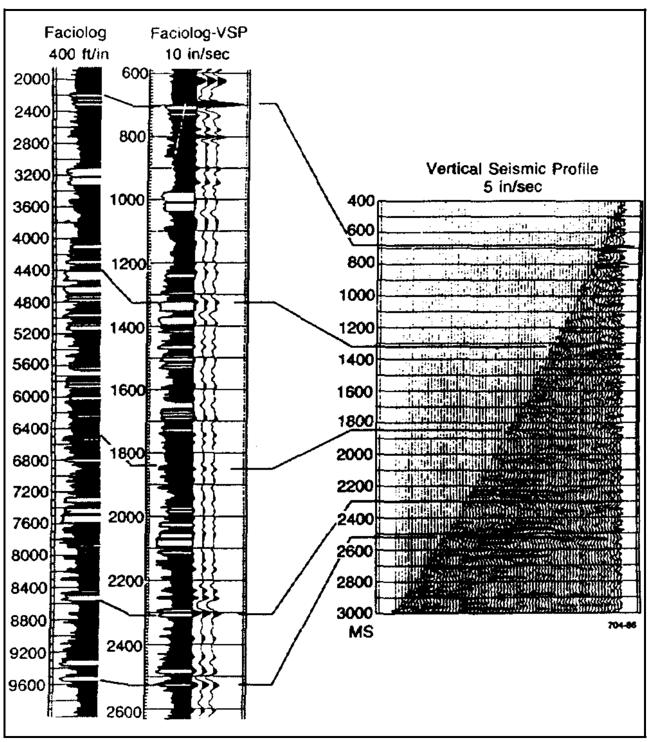


Figure 7-63. Example of tying a VSP to a Facio*log; i.e., a log-derived lithofacies analysis

(b) An example of how a VSP is correlated with existing log information is also shown in Figure 7-64. In this example from the petroleum industry, the repeated sum stack trace is correlated to a time-scaled, log-derived section of the borehole showing lithology, porosity, and hydrocarbon saturation. The lithologic column indicates the volumetric percentage of the major constituent lithologies of the formation. Note that the peak of the seismic reflector yields an excellent fit with the top of the carbonate section (top of the reservoir). Hydrocarbon saturation, shown on the far left, is seen to increase at the top of the reservoir.

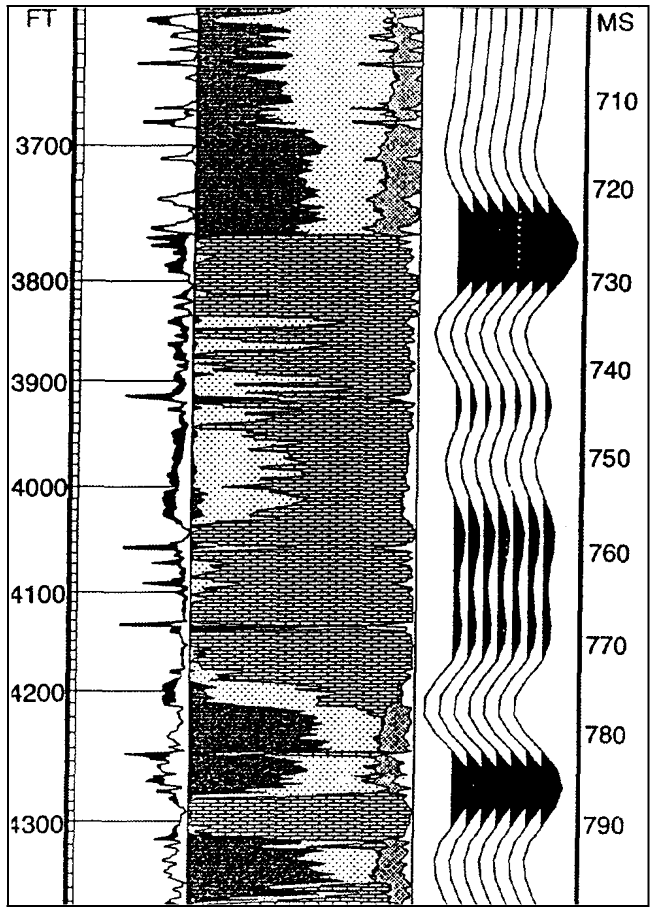


Figure 7-64. Tying the sum stack to log-derived volumetric analysis of lithology, porosity, and hydrocarbon saturation